

# Cryogenic Fluid Management Technology Workshop

## *Volume II—Roundtable Discussion of Technology Requirements*

*Proceedings of a workshop held at  
NASA Lewis Research Center  
Cleveland, Ohio  
April 28, 29, and 30, 1987*

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## **PREFACE**

The Cryogenic Fluid Management Technology Workshop was held April 28, 29, and 30, 1987, at the NASA Lewis Research Center in Cleveland, Ohio. The major objective of the workshop was to identify future NASA needs for technology that will allow the efficient and effective management of subcritical cryogenic fluids in the low-gravity space environment. In addition, workshop participants were asked to identify those technologies which will require in-space experimentation and thus are candidates for inclusion in the flight experiment being defined at Lewis.

The output from the workshop is currently being employed by Lewis personnel to assist the NASA Office of Aeronautics and Space Technology (OAST) in the definition of a comprehensive cryogenic fluid management technology development program.

The principal application for advanced fluid management technology is the Space-Based Orbit Transfer Vehicle (SBOTV) and its servicing facility, the On-Orbit Cryogenic Fuel Depot (OOCFD). Other potential applications include the replenishment of cryogenic coolants (with the exception of superfluid helium), reactants and propellants on board a variety of spacecraft including the Space Station and space-based weapon systems.

More than 100 individuals attended the workshop with 24 nongovernment organizations, NBS, AFAL, AFWAL, and all NASA installations except KSC being represented. Appendix A contains definitions of acronyms employed. The first two days of the workshop were devoted to 22 presentations which provided an overview of the current status of many NASA and DOD fluid management programs. On April 30th, representatives from each organization were invited to participate in a roundtable discussion of fluid management technology issues.

The workshop proceedings have been published in two volumes. The first volume, NASA Conference Publication 10001, includes a compilation of the viewgraph material from each presentation during the first two days of the workshop and a transcription of the questions and answers which followed each presentation. This second volume includes the viewgraphs used during the roundtable session and the transcript of the ensuing discussion.

The roundtable session was organized into eight major technology categories with several subheadings within each category. The discussion of each subheading was initiated by Mr. Aydelott with the aid of a single viewgraph that presented a "strawman" identification of the potential benefits, technical issues, recommended experimental approach, and current programs for each fluid management technology. These viewgraphs were subsequently revised, prior to inclusion in this volume, to reflect any changes resulting from the discussion and to include additional information on current programs provided by the participants.

During the roundtable discussions, no attempt was made to identify the speakers. The editors have attempted to identify the organization represented, when this information was deemed pertinent and a complete list of the participants in the roundtable session is provided in Appendix B to this volume. Some of the roundtable discussion was not always audible or comprehensible.

However, the editors have attempted to document as much of the proceedings as possible and we apologize for any omissions or misinterpretations.

Several technology items were identified as enabling, for future NASA missions, headed by the technologies associated with on-orbit fluid transfer (i.e., tank chilldown and no-vent fill) and those associated with on-orbit pressure control (thermodynamic vent systems and stratification control). It was also agreed that these technologies would require in-space experimentation for development. All parties agreed that the required data could not be obtained in ground-based test facilities including drop towers and aircraft. There was also support for conducting slosh experimentation in a flight experiment.

It was generally agreed that much of the technology required for long-term storage could be developed with ground based testing and analysis but that an integrated system test incorporating all system elements would be desirable. Some system components could be evaluated on the flight experiment. Refrigeration technology can be developed with ground based testing and probably should not be included in a flight experiment.

The editors wish to acknowledge the efforts of Melissa Holzman who converted the tape recordings of the workshop proceedings to the transcript published herein.

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## **I. LIQUID STORAGE/THERMAL PROTECTION SYSTEM PERFORMANCE**

### **A. Thick (> 1 inch) Multi-Layer Insulation (MLI) Systems**

#### Benefit:

- Minimize cryogenic storage system boil-off losses
- Provide system with space debris and micro meteorite protection

#### Issues:

- Effect of launch environment (vibration, acceleration, pressure differential)
- Effect of space environment (contamination, debris, micrometeorites, atomic oxygen)
- Fabrication technique reproducibility
- Degrading effect of pre-launch purge system and ground-handling

#### Experimental Approach:

- Coupon-size MLI specimens can be tested in calorimeters to assess the impact of vibration, acceleration, and pressure differential on thermal performance
- Large scale ground-based system demonstration can be utilized to evaluate fabrication techniques and the effect of purge systems and purge gas evacuation on system performance
- The Cryogenic On-orbit Liquid Depot-Supply, Acquisition and Transfer satellite (COLD-SAT) could possibly be utilized to assess the impact of the space environment on the thermal performance of cryogenic storage systems

#### Current Programs:

- The Air Force Astronautics Laboratory (AFAL) is supporting two contractual efforts; the evaluation of thick MLI systems at Ball and the compact cryogenic liquid oxygen (LOX) feed system demonstration at Martin Marietta.

### Discussion

Is anyone addressing the effects of moisture on radiation shield materials?

I know we mentioned ground-handling effects and I think that's in that same category.

General Dynamics Convair developed an insulation system which is on the tank they delivered to Marshall Space Flight Center (MSFC). That insulation had some kind of an organic coating on the outside that was supposed to protect it from the Johnson Space Center (JSC) salt and moisture environment.

It was organically coated kapton; the coating was General Dynamics proprietary.

General Dynamics has looked at using MLI-type materials, that is, multiple layer materials, not necessarily with radiation coatings on them. They've considered using them as a micrometeoroid and debris protection system; we've actually performed some testing, and, on a weight basis, it is far superior to other things that have been proposed.

Is this current work or is this work that was done 20 years ago?

Oh no, this was about two years ago. We actually tested some MLI; I think it was at JSC, in their facility, using nylon projectiles or something like that.

They did a lot of that work about 20 years ago.

Yes, on the Apollo program, I have seen some samples at Marshall in the museum there. But, no, we've actually tested MLI-type material and then we estimated that if it was multi-layer insulation what the degradation and the thermal performance would be due to damage to the material.

Has that work been published?

No, maybe just in memo form. I think we gave the results to the people at JSC that did the testing for us, and I think we were in communication with the Orbital Transfer Vehicle (OTV) people at Marshall on that. It was Don Saxton I think.

I was going to say that some of the OTV contractors are starting to give us feedback by saying that we may want more MLI than we need for just thermal performance because it does help us out. I don't know if Don Saxton at Marshall might have that information. I am not sure, but I believe a rigorous parametric study has been done recently.

What kind of material was used?

I think we used what we call superflock, which was probably double goldized kapton with superflock spacers. We may have tested some with dacron netting also.

One of the things that occurs to me is that the real issue is that we really don't know what the space environment is. So, it is not so much a question of how the materials are going to degrade, but what is the environment that they are going to see? Is that the general perception of the group? Even if we design a very carefully controlled experiment and we went to space, I am not sure how much general information we would get on the effects of the space environment, for future design, because one of the major unknowns is what is the environment, not what is the response of the systems.



The major uncertainties were in the area of contamination due to the local environment induced around the spacecraft by the Reaction Control System (RCS) or venting. But, in terms of atomic oxygen and ionizing radiation, although those vary due to seasonal variations, that is generally understood.

Does anyone know when they are going to recover the Long Duration Exposure Facility (LDEF)?

I don't think they know if they are. The thing has been out there for several years now, and it has a lot of experiments on it that would give you some idea of material degradation.

My understanding is that the time when they say they could recover LDEF is close to the time when it is going to reenter. The longer the Shuttle is unavailable, the better the chances that it will reenter.

Seems like there is a lot of information right there and it would be worthwhile to be recovered.

Is that why we have to include sensors along with the experiment to determine what role the environment has in producing the degradation, or whatever the effect is that you see in the long-term? Are there sensors to use which actually measure the environment?

The way testing has been done in the past has been to put up a thin metallic sheet and electrically measure the conductivity of it, just like poking holes in it, it is constantly changing. I guess my concern is that it would be a significant experiment in itself; I'm not sure that should be part of the cryogenic fluid management program.

What is the Department of Defense's (DOD) current program in this area?

It is strictly going to be a ground-based experimental program that will provide thermal performance data for thick MLI blankets. I think this is one of the major issues that hopefully is going to be addressed by that program, but it is my experience that fabrication of thick MLI systems is very much an art. You may develop the capability in one or two technicians to do the job very well; It's not clear that they can teach someone else how to do it, or write a report telling someone else how to do it.

Is that system going to include a purge system?

We are designing a purge system that will be included. We won't really do testing of the purge system, other than looking at the heat leak caused by it; we won't be purging the insulation. All the testing is done in a vacuum chamber.

All right, but you will at least address the effect of the installation of the purge system on the performance of the MLI.

On the toroidal tank program there will be a purge system and we will be doing ground-servicing tests in the atmosphere.

Do you plan to do any vibration testing of that insulation system?

That's very likely, yes. There is concern about the effect of the launch environment, but there is also concern about the ground handling of a reusable resupply vehicle. The ground vibrations and induced loads may be more severe than the launch environment.

The concern that I was trying to express here was not only the vibrational environment but also the pumpdown of the system as it goes through the launch. One of the other questions we wrestled with was whether or not it was possible to simulate that in a ground-based facility. It is a combined effect of the depressurization of the MLI in conjunction with the vibration. We weren't sure that we had ground-based facilities that could do that kind of a simulation.

In the DOD test program, are you going to do rapid pumpdown?

Yes, though it won't be combined with vibration.

We'll be doing them one at a time. There will be a depressurization test, there will be a vibration test, and there will be a centrifuge test. If you're putting very thick layers of MLI on large tanks, you've got to be concerned about supporting them and keeping some control over the shifting of those blankets.

We are going to assess the system performance before and after that series of tests so the combined effect of all the tests will be established.

I think the only way you're going to be able to test the insulation system is in a ground installation. There are too many variables; how fast the interstitial gases get out, if the MLI seams open up on you, the effect of vibration and launch loads. You won't know what caused the system degradation if you perform your experimentation on a space craft.

## **B. Low Conductivity Tank Supports**

### Benefit:

- Minimize cryogenic storage system boil-off losses

### Issues:

- Effect of slosh dynamics on disconnect struts
- Effect of thick MLI/Vapor Cooled Shield (VSC) launch loads on support design
- Thermal/mechanical properties of new composites
- Consistent design criteria for spacecraft based on laboratory measurements

#### Experimental Approach:

- Ground development and testing on new composite materials to establish thermal and mechanical properties
- System level demonstration of various support concepts in-space

#### Current Program:

- Ames Research Center (ARC)/Lockheed study completed which addressed applicability of Passive Orbital Disconnect Struts (PODS) to depot tanks
- ARC/Lockheed - ground based system level demonstration of PODS
- Ball/National Bureau of Standards (NBS)  $\text{Al}_2\text{O}_3$ /epoxy composite straps thermal/mechanical properties lab test near completion
- ARC/NBS- $\text{Al}_2\text{O}_3$ /Polyetheretherketone (PEEK) thermal/mechanical properties lab tests near completion

#### Discussion

One of the issues that I have seen in the literature and one that I saw reinforced during the earlier presentations was that it's not clear what the design criteria are for these components. Yesterday we saw a debate about what frequencies you have to design the system for and how those criteria impact the design. What I've seen in the literature is an uncertainty about what allowable stress levels are for composite materials and when you have to consider fatigue characteristics. Those factors tremendously impact the design criteria.

We've made measurements of what the fatigue characteristics of some of these materials are and that's what we're continuing to do with the aluminum composite. However, the mission requirements for your experiment depend a lot on what your launch vehicle is.

Is there general agreement on how close to the ultimate strength of the material you can design?

The fibers have been improved over the last couple of years so that the strengths have gone way up and the allowable stresses have gone up. But, for fatigue type designs it is still one of the key issues. That technology is really coming along, but it's not nearly as advanced as what you have for aircraft structures. I think the design is always going to be vehicle-dependent. For each satellite or each vehicle you build, your basic strut design is going to have to be tailored to your particular application.

On the Cosmic Background Explorer (COBE) and the Infrared Astronomical Satellite (IRAS), we ended up going to NBS who has the capabilities for doing the fatigue tests. We took a sufficient numbers of straps so they could provide a fatigue curve as a function of the load. We then designed a system based on

the test data for that particular strap because it is so material-dependent and it depends on the lay-up also. We just got a massive batch of straps and got test data and you may have to do that virtually for every payload because you are talking about composites that are very dependent on the particular lay-up.

We did essentially the same thing on the Shuttle Power Reactant Storage Assembly (PRSA) straps. A representative number of straps were tested through a very specific load spectrum. But in a flight experiment I don't think you are going to be able to tell the difference between one strap or PODS and another. You are not going to be able to sort out the thermal performance of low-conductivity tank supports with all the other effects on the thermal performance of each tank system.

Much of the technology for both thick MLI and low conductivity supports can be developed on the ground; however you may want to include them on a flight experiment as a demonstration, but I don't think we need to do any specific experiments in space to develop that technology.

You may want some thermocouples in your MLI, but you're not going to want a whole bunch of wires coming out of it.

In this particular area, you might want to include some different types of struts based on what Peter Kittel talked about on Tuesday. They are looking at some new materials for struts, as well as, some different concepts for disconnecting them. The opportunity would be there to fly three or four different types of struts. Any one tank should have identical struts.

I'd like to get back to your original question on this subject; I thought that the genesis code for composite materials was quite advanced. But, I really don't know the answer to how the ultimate stresses of the various lay-ups is input to these codes.

As an observer of some of the problems we had with the safety reviews at Johnson when we were trying to plan an experiment to fly on the Shuttle. They always told us to look at the PRSA as an example of how to design a composite tank support system, and yet the allowable stresses in the PRSA straps were about a factor 3 greater than what they consider to be acceptable in our supports which used the same material.

There is an inconsistency there, and I am not sure it is well founded.

The actual design itself should change depending on the expected environment, but allowable stresses and fatigue scatter factors should be uniform. They should not vary just on the whims of someone who says to make this system more conservative than that one.

I think you're always going to have a problem with that. When you go through something like the PRSA development, you go through a major qualification program and you have a rich experimental history. For a one of a kind item, you don't have that, so you will always require much higher safety factors for your particular experiment.

Within the agency we need a consistent set of design criteria. People that are developing struts for IRAS or Space Infrared Telescope Facility (SIRTF),

even if they are going to fly on a DELTA, should be working with the same design criteria as people that might fly on other launch vehicles.

Let's move on to what I thought was another issue, one that Peter Kittel addressed in his talk. Is there a later version of the PODS concept that doesn't have the sensitivity to alignment that the earlier one did? That was my original concern if we try to apply the disconnect strut concept to a very large cryogenic storage system. The selection of a support concept is dependent on the number of vapor cooled shields and the desired thickness of MLI, but the selection of PODS versus straps really depends on whether or not you have a big change in resonant frequency requirements between the launch and space operations.

If you launch on an expendable launch vehicle, with a high resident frequency requirement during launch, but don't require such high frequency's in orbit, then PODS probably are preferred.

Is that work continuing?

Ames has stopped supporting that work. The six struts that we built under contract have been loaned to Lockheed and are being tested with their own funds. They are building a dewar that could be flown in space, but it is not at the moment space qualified; the ground testing results will be available to us.

Do you really think you need the space environment to evaluate the performance of PODS?

Well, it is always nice to have flown a component even if it is just to confirm that everything you did on the ground was right. We thought we tested most everything we could think of on the ground. We did all sorts of loading and unloading, simulating the thermal contraction effects and fatigue testing, as well as, a whole battery of tests both with individual struts and as a whole system.

So PODS are still a good candidate for inclusion in a large scale in-space system test?

We would like to demonstrate their performance on a flight for confirmation.

I think I agree with what Pat Symons was saying earlier; as far as the struts and thick MLI are concerned, the flight experiment wouldn't be to verify the technology, but it would be to demonstrate the in-space performance of the integrated system.

We have proposed another program to demonstrate PODS, but I'm not sure of the present status of that activity.

Is there any additional work, that anybody is aware of, on the development of low conductivity tank supports?

There is some work being done on alumina/epoxy materials. On MSFC'S cryogenic bread board tank, we did have low conductive struts which had MLI in the core section of the struts.

### C. Combined Foam/MLI Insulation System

#### Benefit:

- Minimize boil-off both pre-Launch and on-orbit

#### Issues:

- Reusability
- Foam contamination of MLI

#### Experimental Approach:

- Ground-based testing provides adequate system performance data

#### Current Program:

- On-going Langley program studying encapsulated foam and its response to thermal/mechanical cycling. Current push towards developing lower density foams and the use of foam as internal insulation.

#### Discussion

In the cryogenic insulation systems, which are obviously of interest here, there is the Rohacell insulation program where Langley has been taking this rather high-density foam and encapsulating it in kapton sheeting and metal to simulate a tank wall. We then tested the material under thermal or axial stresses.

The Langley program is currently looking at lower density foams and what do we do about air condensation at gaps, since the encapsulated pieces of foam may be 40 by 40 inches with gaps in between panels. Also, we are looking at the use of this material as an insulation internal to the tank. Evacuated, all-titanium honeycomb makes sense as a cryogenic insulation for certain kinds of missions, where you're talking relatively short time to orbit; of course, we are not talking about a horizontal launch vehicle like the National Aerospace Plane with significant duration to orbit. For load bearing multi-layer insulation, there are some weight advantages; however, you must address the problems of making it hold a vacuum and withstand the 15 psi delta pressure on the ground. The task that has been going on with high temperature foam involves testing it at elevated temperatures with axial loads and then a 100 cycles between liquid nitrogen temperature and the high temperature with some cycling down to liquid hydrogen temperatures. Having gone through the cycling successfully, we found many foams that worked fine and then they just fall off the tank and all kinds of other things.

The reason we are interested in these materials is the high temperature properties. Can they withstand cycling to +400 degrees Fahrenheit on one surface and -400 degrees on the other surface?

Multi-wall insulation is just a series of dimpled sheets of low conductivity material. This work has been going on at Langley for some time, and there are some nice advantages to it; it is obviously a high temperature system, so we can have very high temperatures on one side and cryogenic temperatures at the other. The problems with multi-wall insulation involve encapsulation techniques to form a vacuum, since without a vacuum you start getting convection currents inside the material. At atmospheric conditions it doesn't hold a candle to a lot of other systems, but evacuated, and considering that it is load bearing, we figure it may be competitive with load-bearing MLI or vacuum-jacked MLI systems.

What is your funding source for the insulation work?

Some of it is going to come from the Strategic Defense Initiative (SDI) and some from the Office of Aeronautics and Space Technology (OAST); I believe.

The cryogenic efforts at Langley have been fairly small and they are only now beginning to expand because of the thermal-structural aspects of insulation systems.

How do you impose your thermal loads?

That depends on what we're after. We can study simple thermal stresses by restraining the system and using quartz heat lamps on one side and cooling on the other side.

In terms of an earth-to-orbit tanker, you might like to combine a substrate insulation for pre-launch performance, with the multi-layer insulation so that you would have at least a reasonable on orbit heat leak. It seems to me that one of the key concerns with the substrate is that it might become a contamination source for the MLI and you won't get the on-orbit performance that you would like. Possibly some of these all-metallic, substrate materials would alleviate that concern.

If you were planning to use a substrate material with MLI, during the bakeout process when you're trying to get rid of all residual gases, it could be done under a vacuum situation and I think you could assure yourself of baking out any potential contaminants. You could also include a gettering material of some sort.

What about differentiating between internal and external foam? Has everybody given up on internal foam insulation?

Are there obvious advantages to external rather than internal?

Langley is still interested in internal foam for the national aerospace plane. We're talking about running a hot structure with the insulation on the inside of the tank. Remember we're talking about the use of horizontal tanks where you can potentially have a lot of surface area that is warm. Under a slosh situation, you don't want to get large changes in pressure, so internal insulation makes a lot of sense for that type of operation. For a vertical launch vehicle, I'm not sure it's as important. In the internal configuration however, even with insulation encapsulation, you get hydrogen diffusion into the foam; it's not a

perfect barrier. Consequently the foam has the conductivity of hydrogen at the very low temperature.

In summary, foam is better outside the tank for conductivity reasons and better inside the tank for avoiding pressure spikes.

For the applications this group is looking at, the tanks are either going to be empty when they're launched or they're going to be fully loaded. We may not have to be concerned with the dynamic problems.

It is a problem for the Shuttle external tank, principally at lift-off, but also during ascent.

The liquid goes around and around in the tank.

There were multiple investigations on internal foam insulation concepts performed back in the 60's and early 70's before the funding dried up. A couple of years ago General Dynamics Convair (GDC), on an IR&D program, spent about a year and a half looking at using an open cell internal foam and got very encouraging results. We were able to get stable vapor layers to exist in the foam and got quite good thermal performance. Work needs to be done on adhesives, but we felt the results achieved were very promising.

If we're talking about using as much as four inches of multi-layer insulation, what are we doing for the ground-hold condition? Is that going to be a helium-purge system?

That's part of the reason that you would consider using one of these foam substrate systems, to eliminate the need for a helium purge of the MLI.

You've got to be careful that the foam external surface temperature doesn't get below about 140° Rankin, or you're going to get nitrogen condensation, so I think when you talk about a foam and multi-layer insulation combination; there's some limitation on how much multi-layer insulation you can employ.

For the tanker application, I'm not sure you would have a thick multi-layer insulation blanket.

You may be talking mission times on the order of a few days.

Most of the NASA concepts for a Space Station depot indicate that the tanks will be launched dry. They would have thick MLI blankets, but you don't have to worry about ground-hold conditions. What I'm hearing from the military is that they may have a requirement for both launching a system wet and then wanting to stay in orbit for a long period of time. They may be the ones that want to combine some kind of a substrate material with a thick MLI blanket.

Is the motivation for eliminating the purge system based on a desire to reduce system weight?

I think you are going to be forced into using a helium purge for the military applications, as opposed to a foam substrate, because you just cannot prevent the foam from getting too cold and possibly cryopumping air or nitrogen.



The study that Lewis supported at Boeing a couple of years ago indicated that, even if you did put on enough foam to preclude condensation of nitrogen, there was actually a weight advantage to the combined system. Admittedly, that study did not go into any great depth of detail; they were just concept studies, but the results consistently showed an advantage for the combined system. The results are highly influenced by the ground support scenario; the question is, can you continue to load hydrogen right up to launch, or is there a loading cut off point several minutes prior to launch?

The other big factor that you mentioned is how long your mission is?

Yes, that is also very important. Right now, for the Centaur as an example, the missions are relatively short.

For some of the fairly ambitious Earth to geosynchronous orbit (GEO) missions, including return of payloads, the missions generally involve something on the order of a seven day total trip. The mission times are extremely short compared to a Space Station depot that will be on-orbit for years.

I think everyone needs to be careful, because in many cases each system will have very different requirements and what's valid for the Aerospace Plane may not be valid for a tanker or a depot tank. We may have structures that can double as vacuum jackets, and you can take advantage of that structural weight. There are a lot of options for each system and we may have to design for each particular case.

On the other side of the same issue, maybe we can't afford to develop unique systems for every spacecraft.

We won't be able to afford not too.

We may have to live with technology that was developed for some other application even though it might not be optimum for our particular purpose.

Let's get back to the use of internal foam again for a second. There are design applications for internal foam where it is, without a doubt, the best and possibly the only solution. When you have local attach points on your tanks that can't be effectively insulated from the outside, it may be that the only way to dissipate the heat input is to accept the resulting increase in boil-off. A good alternative is to put a little bit of foam insulation on the inside of the tank at that point and nearly eliminate the heat short.

The insulation around the support area is one of the main contributors to the heat leak into the tank. That problem can be considerably simplified if you use a vacuum jacket. If most of the larger tanks are launched dry, a vacuum jacket will not be a weight limitation.

Certainly, if we are talking about Shuttle transported tanks, we may find that we actually have volume-constrained payloads. In such a case, we don't have to be concerned about weight penalties.

For Shuttle launches of loaded tanks, you want to have good ground hold capability so that you can avoid tying into the T-zero umbilical.

So for tankers, the vacuum jacket is the primary way the Shuttle operators would want to go.

For the Centaur, they conceded that they would continue to pump hydrogen into the vehicle almost right up to launch.

That was definitely a special case.

You'd like to avoid that situation, and as a result, it would certainly drive you to some kind of a good ground insulation system. It may still have a couple of orders of magnitude lower performance than your space insulation system, but much better than the Centaur.

Liquid helium systems are typically loaded two days prior to launch.

Well, that is the other extreme.

Two days is even pushing it; sometimes it is closer to two weeks.

If we were building a Space Station depot tank that we wanted to transport fully loaded and they told us to design them so they could be loaded two days before launch, I think everyone would agree that would be an unreasonable requirement. We are talking about tanks that would fill the cargo bay of the Shuttle; they would have to be vacuum jacketed. Obviously, there would have to be negotiations between the depot developer and the Space Transportation System (STS) operator to establish a reasonable tank loading scenario.

#### **D. Light Weight Vacuum Jacket**

##### Benefit:

- Minimize system weight, boil-off and on-orbit degradation

##### Issues:

- Design criteria

##### Experimental Approach:

- Ground-based structural tests and large scale integrated system demonstration

##### Current Program:

- Air Force Astronautics Laboratory (AFAL) plans for fiscal 1990 include the start of a three-year program for developing a vacuum shell, including weight and storage time break even trade studies.
- Langley's program for fiscal 1987 includes load-bearing MLI for lightweight insulation.

## Discussion

The idea of trying to develop a lightweight vacuum jacket seems like an idea that keeps coming up and then it goes away again. In the last couple of days, I've heard that the military was very interested in launching systems completely loaded with cryogenic liquids, and yet they would like those systems to have long term orbital storage capability. Is the development of light weight vacuum jackets an area that you are pursuing, recognizing that vacuum jackets may be the only way to meet both of those requirements?

AFAL's planning on investigating that in our 1989 budget.

That's a very important issue for ground-based, reusable vehicles, because if you have to bring the system back loaded due to some kind of abort, you will need the system to have good insulating values on its way home.

Based on the charge to conference participants we heard yesterday that said you're going to be using supply tankers to load your depot, this may very well be a key issue for that as well.

There's a program at Langley that is about to start looking at load-bearing MLI. The program is not only being driven by the needs of reusable space craft for supplying Space Station storage tanks, but also by the needs of the National Aerospace Plane. As I remember, there's a subcontract to Beech for the work. It is really a load-bearing MLI system; I guess you would say it is a flexible vacuum jacket.

Most of those systems have pretty poor performance compared to thick MLI, however.

Don't you mean terrible performance?

Yes.

I think they might be suitable for an earth-to-orbit transport type vehicle where you have a short mission time.

The idea that I was trying to suggest here was something that came out of the analysis that Nakanishi did. The results suggest that by the time you put on enough protection for debris and micrometeorites, you might have something that's similar to a vacuum jacket. So, it might make more sense to try to design a vacuum jacket that will provide the on-orbit debris and micrometeorite protection as well.

If you're going to do that, why not look at this thing as a composite tank wall? Maybe you can lighten up your complete tank system.

The disadvantage of that approach is that you will degrade your insulation system because of exposure to the space environment. Where as, if you put your shield on the outside of the insulation system, which is what a vacuum jacket is, then your insulation system won't degrade with time. That means carrying a great deal of dead weight around.

Well, that really is the key issue; can you afford the weight penalty associated with that type of a system.

It depends on the design; possibly the vacuum jacket shell can become your vehicle structure and carry the thrust loads during launch.

I think it's very vehicle, mission, and concept dependent.

For the space-based OTV design concept that Boeing is looking at, the micrometeorite shield is in fact the structure and the external shell of the spacecraft is the load-bearing structure. The tanks are hung off that shell. If you want to go to a vacuum shell, then that structure probably doesn't make sense, because you can't get in and out of it and you can't seal it up properly. I think for a ground-based system you probably want the shell integral with each tank, so you don't have to break into it to get at the lines and what ever else is in there.

Once again, the DOD is planning to support work in this area.

Langley is not working directly in this specific area, but we're working in the area of cryogenic tank structures and insulation systems, especially for reusable space boosters, including the National Aerospace Plane. There's a lot of overlap in this work, because when you start going after minimum weight, you start looking for dual-purpose systems. In the Thermal Protection System (TPS) program we are looking at all-metal, multi-wall, honeycombs with fiber insulation. Heat shields made of carbon-carbon is a big item with us. In durable TPS concepts, we spend a lot of time looking at titanium and advanced titanium honeycombs. We always compare these to the reusable insulation from the Shuttle as we strive for higher and higher temperatures. When you start talking about reusable systems, the higher the temperatures of the TPS the less heat you're going to let into your vehicle, so you're always going after higher and higher temperatures. You're willing to take a weight penalty for that. For tank structures, work on developing evacuated titanium honeycomb is a fairly large program. The thermal performance of the material is being determined experimentally at the National Bureau of Standards. There are some thermal-mechanical tests going on at Dryden. We are also looking at how you join honeycomb panels; it's not a trivial matter. We are looking at multiple materials, of course. We are looking at composites, metal matrix composites, titanium, aluminum, hybrids with insulation in multiple layers, and aluminum-lithium. The reason we're interested in aluminum-lithium is that it offers higher strength and higher thermal performance and temperature, and does it at a lower density than some of the best aluminum systems. The real kicker is that it may be possible to superplastically form this material. This means, for example, for those of you who are familiar with the external tank and all the internal ribbing inside the tank, it might be possible to extrude or superplastically form aluminum-lithium in very, very large pieces. We will be looking at joining techniques. We'll look at how you weld it; we'll also determine what the physical and mechanical properties are.

What are the allowable strains on that type of material?

I'm not the one to answer your question, but they're just beginning to look at that. They are going after very small grain sizes, and now you're starting to work in an area of powder metallurgy, so there's a lot of basic material work

that is going to have to be done. We think that even though it's going to be an expensive alloy, if you consider only the cost per pound for material in the finished product, it's system cost will be insignificant compared to all the labor that is required to fabricate large tanks with Shuttle technology.

The titanium honeycomb joining program has evaluated liquid interface diffusion bonding, spot welds, and electron beam welds with the objective of not degrading the base material.

The program is winding down, and we feel that we proved we know how to take very large panels and put them together. The tests that are currently going on at Dryden are testing bonded panels both thermally and loaded structurally. It is not an easy thing to take a honeycomb panel and apply clamps to it without edge effects and localized damage.

An area that needs some work right now is that a launch-induced vacuum jacket failure is considered to be a credible failure by JSC; I have a hard time living with that. Why would that be more credible than a failure of any other pressure vessel?

You definitely need to address that, because vacuum jacket design is a big driver on the entire system design.

That will be a long, hard fight; that is our feeling.

We have supercritical hydrogen tanks on the Shuttle, and if they fail, the Shuttle is gone. Why is it that we can accept the failure risk associated with the vacuum jacket on the PRSA tanks?

The PRSA is an element of the STS, as opposed to a payload that is being carried up by the STS. The STS does not permit you to consider them to be the same.

They won't, but I think, as a community, we should be putting pressure on the STS operators.

The possible solution to the problem is to use all of the things that we have been talking about; use some type of substrate insulation to provide a back-up in case of a failure of the vacuum jacket so that you couldn't get excessive heat rates to the tank and then also fill the vacuum annulus with MLI.

Is this not also something that could be addressed in a qualification program? If adequate design margins can be demonstrated, the possibility of failure can be eliminated. It seems that this collapse or failure of vacuum jackets is in the same ball park; you are going to have to demonstrate a certain design margin for each concept and vacuum jacket material you apply. That is the problem; there is not a lot of experience, so there is a lot of conservatism. I agree with you, but that is not the stand that the STS operator is taking.

JSC is taking that stand for the reason that was pointed out; we don't have the background information to prove that it is not a credible failure.

#### **E. Para-to-Ortho Conversion of Vented Hydrogen Gas**

##### Benefit:

- Minimize cryogenic storage system boil-off losses

##### Issues:

- Weight penalty (catalyst activity)
- Catalyst contamination/poisoning
- System integration

##### Experimental Approach:

- Material testing to determine catalyst activity and life
- Ground-based component and integrated system tests to demonstrate performance

##### Current Program:

- Development of a more active catalyst will be performed by Air Products under contract to Wright Patterson Air Force Base in Dayton, Ohio. Work will be performed over a two year period starting in the summer of 1987

#### Discussion

This work is being supported somewhat indirectly by the National Aerospace Plane. Lewis Research Center is also doing some in-house work in this area. We should just make a note of the fact that the National Aerospace Plane program is supporting this work. My thinking is that if we can learn how to integrate this kind of device into a vapor-cooled shield, it should be a candidate for inclusion in a sub-scale depot one-G demonstration test. I am not sure, however, that this program should be directly supporting work that is looking for new catalysts.

Did you say that the Air Products contract dollars were from the National Aerospace Plane program?

Right, but I think it is somewhat indirect; the money is from their general research and technology program dollars rather than being specifically from the National Aerospace Plane program.

Is the work at Lewis being supported by the National Aerospace Plane Program?

Yes, the work that we are doing is coming directly from the National Aerospace Plane.

Is anyone else aware of any other work that is being supported in this area?

Lockheed did some work for Goddard a number of years ago.

I think that work has been well documented. It is probably the basis for some of the current work.

#### **F. Multiple/Coupled Vapor-Cooled Shields**

##### Benefit:

- Minimize cryogenic storage system boil-off losses

##### Issues:

- Weight penalty
- Thermal/structural integration with complete system (particularly MLI)

##### Experimental Approach:

- Using large coupons, perform thermal and structural tests, supported by analysis, of candidate VCS/MLI concepts
- Ground testing is sufficient, with selected features being implemented into a large system demonstration program

##### Current Program:

- General Dynamics is including VCS/MLI features in its hydrogen tank systems-level ground development test program

#### Discussion

Considering the use of multiple vapor-cooled shields, the concern I had was that all the analysis is generally based on steady-state assumptions. That is a reasonable approach if you have vacuum-jacketed systems.

For SIRTf and other similar systems, Ames analytical models include the transients associated with cool-down.

I was thinking more of the fact that the boundary conditions are going to change with time due to the effects of atomic oxygen and debris, for example. My concern was that if you optimize the location of your vapor-cooled shields for either the initial boundary condition or the projected mid-life boundary condition, you will then have non-optimum performance at other times during the mission; isn't that true?

It is true except that the optimum vapor-cooled shield position doesn't

change very much with surface temperature. The difference in system performance isn't that great.

What does come into play is the number of shields which you think are optimum and the corresponding weight trade-off. Optimum shield location also depends on the interstitial pressure.

We always have a high vacuum for the helium storage systems, so we don't worry about that.

Are there any other issues associated with the use of vapor-cooled shields?

For some applications there is obviously an unacceptable weight penalty. At one time, people thought there might be a gravitational effect on the internal heat transfer coefficients, but the general perception now is that that is not true.

Lockheed has done some experimenting with lightweight aluminum honeycomb structures to reduce the weight of vapor-cooled shields.

Was the vapor going through the honeycomb?

No, tubes were just bonded on. The purpose was to give you enough strength to withstand launch, while keeping the weight down.

When you use the single-shell type of vapor-cooled shields, they need stiffening features for strength. If you put standard rib-type stiffeners on them, the ribs tend to interfere with the MLI system. There is possibly design work that needs to be done on vapor-cooled systems not in terms of how well they work, but in terms of how to integrate them with MLI.

Once again, vapor-cooled shields are a candidate for inclusion in a One-G storage system demonstration.

Well, yes and no. You can do thermal/structural tests of samples of what you consider to be a representative cross section of the MLI and the vapor-cooled shield with all the structural features for attachment and stiffening; it's maybe a couple of square feet in area. However, I think there is a lot of parametric study required first to support your selections of various design approaches for testing.

Are we going to be addressing coupled heat exchangers at all?

I had it on the chart but we didn't talk about it.

Are there different technical issues associated with coupled heat exchangers?

The issue is whether or not you would consider coupled heat exchangers for incorporation into the flight experiment? If you did, you'd probably want to load something other than liquid hydrogen into one of the receiver tanks at launch in order to demonstrate the benefit of that type of system.



The real issue is whether we need to take VCS to space or can we do enough testing on the ground to convince ourselves of how they will perform in space? I guess I am of the latter opinion; I think we can probably do most of that kind of work on the ground. I presume that the VCS performance is not that gravity dependent.

Not the thermal performance, but it seems to me that there are some real design issues associated with the shield structure and its plumbing system. It can't be pushing against the MLI and causing a heat short.

But, that is not different than the design issues associated with cooling an oxygen tank with the oxygen boil-off. What has been suggested is that you might want to take the hydrogen boil-off and use it to cool the oxygen tank, or vice versa.

Are there any different technical issues associated with that concept, or are they essentially the same? Really the big issue probably is safety if you want to route the hydrogen vent vapor into the oxygen storage system.

**G. Low Thermal Conductivity Components (instrumentation, valves, disconnects, plumbing lines)**

Benefit:

- Minimize cryogenic storage system boil-off losses

Issues:

- Reliability (redundancy required)

Experimental Approach:

- Individual component development and test programs for valves, disconnects, and plumbing lines
- Composite materials for low thermal conductivity plumbing lines
- Components integrated into large storage system ground-based demonstration

Current Program:

- Cryogenic, motor-operated valves being developed by Utah State University for GSFC
- Low heat leak, cryogenic disconnect being developed for Superfluid Helium On-orbit Transfer (SHOOT) program by JSC
- Air Force funding Rockwell to investigate graphite/aluminum composites for lines
- Cryogenic motor/pump under test at NBS and Creare for ARC

## Discussion

This is an area where the people who have been working on liquid helium systems should be a good source of information for our program. The work you are doing on disconnecting struts was presented earlier. I assume that low conductivity is a real design driver for your valve development work as well.

Well, it's not so much low conductivity as low power dissipation; it's low total heat input to the system. The whole valve, including the motor, is designed to work at liquid helium temperature and then the wires for power and control are the primary heat conduction paths. For some of the other cryogenics, you have the option of locating the valve driver remotely, but then you have the heat-leak penalty associated with the valve driver.

Is anyone supporting work on composite line materials? I know there was work done by NASA 15 or so years ago, but, to my knowledge, no one has ever picked up on that work and tried to apply it to a system. Lewis supported work on composite overwrapped feed lines, but they were all just straight sections of lines. That is a lot different from trying to put the concepts into a complete system.

There is some work being supported by DOD on metal matrix materials for high pressure lines as a weight-reduction technique. They are looking at the use of graphite aluminum and considering methods of attaching it to end fittings. This work may address some of the structural problems associated with making low heat leak, polymer-type lines.

The SHOOT coupler employs composite materials, but GSFC doesn't currently have any ongoing programs in this area.

Has the work that is being done on helium valves in Utah State University been published anywhere?

Not yet.

I think we would like to have people aware of the fact that you are supporting that work. The work to develop valves for IRAS has been published. The SHOOT coupler development is work that is being supported by JSC.

Is there a contract in place right now?

There will be. We have received proposals and expect to have a contract soon, probably in July. (Contract awarded to Moog.)

That development activity is for an Extravehicular Activity (EVA) disconnect. It is going to have to evolve into an automatic, remotely-operated disconnect system to be of any benefit.

That requirement is part of the Request For Proposal and was part of the selection process. The design we selected is amenable to automatic and remote operation.

## **H. Large High Performance System Demonstration**

### Benefit:

- Confident system design criteria, fabrication techniques, and performance projections

### Issues:

- Wide variation in performance projections

### Experimental Approach:

- Large ground system demonstration and include individual technologies as part of flight experiment

### Current Program:

- AFAL thick-MLI program to produce two 10-feet in diameter test tanks for use in demo/evaluation of MLI, Struts, VCS, and refrigeration systems
- AFAL compact cryogenic feed system program to demonstrate thermal-protection system performance for an OTV LOX tank on a Toroid 13-feet in diameter with a 6-feet in diameter cross section

## Discussion

The first issue we need to address is the identification of the components that might go into a high performance storage system demonstration. On the previous group of charts I was trying to identify the significant components that might be part of this system demonstration.

Are you talking about a flight demo or a ground demo?

Let's address that after we make sure that we have talked about all the components that might be included in a thermal protection system.

In reviewing the literature, I found several studies which attempted to provide projections of boil-off from a depot type tank. The results of those studies indicated about a 6-to-1 variation in projected boil-off from a large hydrogen storage system in the Space Station environment.

What was the cause of the discrepancy?

It was a combination of a lot of things. For example, is a purge system employed, or are the tanks launched dry? Does the system have a vacuum jacket? What MLI materials are used and how thick can the blankets be?

Are these losses on-orbit only or are the losses associated with the earth-to-orbit transport phase also?

No, the studies dealt specifically with the on-orbit system performance only.

I found some studies that were based on the use of silverized MLI. That doesn't make a whole lot of sense if you've got atomic oxygen in the environment. Even though we know silver is one of the best MLI reflector materials, it is also one of the worst materials for degradation due to atomic oxygen. There is also a lot of hand waving involved in what storage system performance people think can be achieved, and my thinking is that the system performance uncertainty is the major justification for a large storage tank demonstration. It has been a long time since anyone has built a large, high-performance cryogenic storage system.

One of the big issues is the venting of cryogenics in the vicinity of the Space Station. If we can achieve a very good system thermal performance, you can think of things to do with the boil-off. It can be used for propulsion, life support, or to generate additional power. But, if you are on the high end of the projected system performance, you can't use all the boil-off no matter how big an imagination you have. Poor system performance also drives the refrigeration system development program. If you really can't build a good performing storage system, then maybe the use of refrigeration is the only alternative.

I think the demonstration you are going to do is very dependent on the mission.

I agree, but NASA's primary interest is the depot. The depot is a long-term cryogenic liquid storage facility, located in the vicinity is the Space Station, whose purpose is to supply cryogenics for refueling OTV's or to support a manned Mars mission. The military does have an interest in developing similar capability but for different missions.

But, the depot could very well go up dry. On the other hand, the tanker or Strategic Defense Initiative (SDI) tank may go up wet and yet have the same kind of on-orbit requirements. A wet or dry launch scenario is going to effect your system design and, ultimately, what your system demonstration should consist of.

Are we going to try to demo an OTV tank, a depot, and a tanker, or just demonstrate the technologies? I think it will make the individual experiments different depending on what we decide to do.

I would like to suggest that we recommend that the large system demonstrations be done only on the ground and that we try to demonstrate specific technology on the COLD-SAT, if in-space testing is required. This suggestion comes from a cost point of view; I'm not sure NASA could afford to fly a prototype depot. We can demonstrate PODS, vapor-cooled shields, para-to-ortho conversion, or other specific technologies in-space. To actually put a large storage system in space and leave it there for several years to assess the impact of the space environment on the system performance would probably be too expensive.

Is this an area where the DOD feels differently? Maybe there is a possibility that we could enter into a joint program to provide a large scale cryogenic storage system demonstration.

The DOD has some interest in the out years, post 2000, for some kind of a space storage depot for resupplying spacecraft. Whether the DOD depot would be in a Space Station-type orbit or whether it would be in an orbit with a higher inclination have not been established. There are no firm plans. There are some obvious technology requirements, but, in general, they're pretty fuzzy right now.

Would you generally be supportive of a NASA program if it included a large scale cryogenic storage system demonstration on the ground?

The DOD program plan currently includes only ground demonstration. Why is there a long term cryo storage goal for the depot if you're performing periodic resupplying?

The long term storage requirement really doesn't fit the application. What we are talking about is trying to minimize boil-off. The problem is you can't figure out either what to do with the boil-off or how to get rid of it.

You can't afford to throw the boil-off away either.

In addition, you want your system to last for at least ten years without refurbishment.

What do you mean by a large-scale demonstration?

The demonstration system is going to have to go in a big vacuum facility and there aren't too many of those around.

I think that existing ground-based test facilities probably would constrain the size of the system allowable.

MSFC has a 20-foot test chamber.

The only problem is that you're going to probably want to run this test with hydrogen, and, since it is a hazardous operation, most test chambers are not suitable.

MSFC's vacuum chamber is qualified for hydrogen.

General Dynamics has a ten foot hydrogen-qualified test chamber.

What about the facilities at Plumbrook?

That's another possibility.

The continuing problem we have using Plumbrook facilities is that every other day NASA management says they are going to close the place.

I view the COLD-SAT program as an opportunity to do systems level demonstrations. It may not have all the features of a storage depot, but it will include a couple of different tanks, so you've got the opportunity for including most of the technologies that will show up in a depot or an OTV. So, I'm a little confused about saying that we ought to also have a ground demonstration program. Won't the COLD-SAT be sort of a systems demonstration itself?

The problem is that to meet those objectives, you'd like COLD-SAT to be operational for a long time and also be fairly large scale; I am not sure the agency can afford that type of a program.

Also, we don't really know how long a test is required. If you want to look at the long term degradation of coatings, you may want to take measurements for as long as five years. Data is coming back from a couple of Air Force satellites that are at fairly high altitudes. They've been taking coating degradation data for years and every year they present results at one of the conferences, usually Aerospace Sciences and Thermophysics. If you're looking for data on how well active components like pumps, compressors, and valves will hold up; you can do that type of life cycle testing very easily on the ground. However, if you're worried about the effects of the space environment, you've got to go up there for a long time. You don't need a systems test for that, however, you may be able to do that with samples.

If you want to use a hydrogen calorimeter as a means for evaluating the system degradation, what you find is that even with the most optimistic projections for system thermal performance, you have to have a really big tank or you won't have any hydrogen left after one or two years.

We took a look at what you might be able to accomplish in a year or two of on-orbit testing, but our concern is that that's probably not long enough to assess the impact of some of the key environment effects. You'd have to go to a Centaur or a Titan launch vehicle to get a big enough hydrogen tank so that it would still contain some LH<sub>2</sub> after several years.

That's probably true if you want a test time of significantly more than six months.

If there is a need for doing a system performance test on the ground, why not make that an extension of the thick MLI tests that the military is currently supporting?

I think that should be the plan, and our role is to see that both NASA's and DOD's interests are incorporated in that program.

It would be good if you could accomplish that, because in the past there has been no standardization of testing equipment or experimental conditions. As a result, it is often difficult to correlate the results from different sources.

What's the feeling on the differences between the Air Force and NASA ground demonstration program requirements? Are there a sufficient number of things the Air Force program won't look at that NASA wants to look at so that we will have to have two, long-term cryogenic system tests?

Right now, I'd say no. I think our needs are very similar in this area. The exception might be that the military requirements would dictate the use of a vacuum-jacketed tank and that would eliminate the problem of tank sizing to fit existing ground-based facilities. However, a vacuum-jacketed tank could still demonstrate the overall system performance that would be of interest to NASA.

Right now, they're not thinking about incorporating the system approach into their thick-MLI blanket testing program, are they?

I think that's in the plan, but it's not currently funded.

Do you plan on putting a vapor-cooled shield on the tank?

Yes, eventually.

## II. LIQUID STORAGE/PRESSURE CONTROL

### A. Thermodynamic Vent Systems (TVS)

#### Benefit:

- Controlled cryogenic storage system operating conditions

#### Issues:

- Performance of alternate TVS concepts and heat exchanger locations

#### Experimental Approach:

- Ground-based transfer system tests and COLD-SAT will provide evaluation of alternate TVS concepts

#### Current Program:

- Design concepts based on liquid helium storage system technology can be applied to provide depot needs

#### Discussion

None

### B. Fluid Mixing

#### Benefit:

- Minimize temperature stratification
- Enhance TVS performance
- Avoid unpredictable pressure surges

#### Issues:

- System complexity, reliability, and efficiency
- Low-G fluid dynamics
- How much mixing is required
- Optimum mixer size
- Degree of stratification that occurs in tanks for different applications



#### Experimental Approach:

- One-G and Zero-G testing to provide detailed data to validate models
- Establish how stratification occurs
- Measure mixing that occurs naturally and by disturbances
- Test jet mixers to determine liquid velocities and energy addition to fluid

#### Current Program:

- Research grant (NASA Lewis) at MIT to study condensation fundamentals
- Boeing IR&D on One-g jet mixing to induce condensation (using Freon II)
- Shuttle/Centaur TVS with internal heat exchanger and mixer

#### Discussion

I think the most important issue is the low-gravity fluid dynamics.

Before you can design something to eliminate a problem, you have to know what the problem is. It seems like temperature stratification is a area of study which pretty much died in the mid sixties.

That's one of the things we are trying to study via a grant at MIT with Professor Sonin. There also have been a number of IRAD activities studying fluid mixing phenomena.

This is also a significant problem for the National Aerospace Plane, and I think there's going to be quite a bit of work looking into that whole situation.

Where do think there'll be a lot of work? Do you think all the air frame contractors are going to be addressing stratification problems.

I don't know if all of them are, but McDonnell Douglas definitely is.

There's a related question to this necessity for mixing. It's not only related to thermal stratification, but also to ullage control or the thermal interaction of the liquid with the container walls. As you mentioned, we really don't know how bad the problem of thermal stratification is for the very long-term storage problem. I presume that the sizes are quite large and that the disturbances that will be taking place are going to be very small. So, we can't say that the liquid is quiescent, since we just don't know. But, you will have a ullage space which will be established when the tank is filled, and that could be at one location. However, even with MLI, you can't make the heat leak completely uniform, so you're going to have hot spots, hot being a relative term. In time, you're going to generate vapor spaces at these locations. The interface temperatures will

always be the same; they will correspond to the total system pressure. If one hot spot is a little bit hotter than another one, the rate of vapor formation is going to be different, and that's going to set up thermal gradients. If the temperature variations are small enough, you don't have to have the mixing, but we don't know that yet, as far as I know. I am suggesting a very general basic study that I believe should be done. Some work was started back in the mid-sixties, but it was never completed.

Maybe we need to identify a separate research requirement devoted simply to the study of the stratification problem so that we would know what the requirements on fluid mixers and thermodynamic vent systems are.

One of the key issues with thermodynamic vent systems is heat exchanger location. Do you put the heat exchanger in the tank in conjunction with the mixer which stirs the tank contents? Do you selectively wall mount heat exchangers on the tank to control the stratification, or can you intercept enough of the heat before it enters the tank with vapor-cooled shields so you don't have to worry about stratification?

I think the Lewis view is that it will be very difficult to prevent localized hot spots due to heat conduction through tank supports or instrument leads, for example. Consequently, you are going to have some stratification in the tanks, and we believe that for large tanks you probably will have to have some sort of a mixer to minimize the stratification and allow effective tank pressure control.

Lewis has done some studies looking at flow patterns that occur under low gravity conditions. The real gravitational environment issue is whether you can perform sufficient testing on the ground in order to understand the flow patterns that occur in a tank. I guess Lewis' feeling is that you probably cannot. The input power that would be required to provide liquid circulation and mixing and how effective that mixing is for controlling tank pressure is very much G-dependent. I think we see a need here to do in-space experimentation supported by analytical efforts to really characterize this problem.

On the long-term cryo study supported by MSFC, General Dynamics started out with an internal heat exchanger concept like Shuttle/Centaur would have employed, because we were familiar with it. We quickly discovered that, even with what I would consider to be questionable assumptions about the period of time you would have to have that mixer on, we were putting too much energy into the tank with the mixer and that we had to go to a wall-mounted heat exchanger configuration. That doesn't mean you still don't have to mix the liquid in the tanks; it means that you don't have to mix continuously for your TVS system to operate properly. If you have vapor-cooled shields you will want to operate your TVS system continuously. I think you need to look at the specific application before deciding on the type of TVS system to employ and the corresponding liquid mixing requirements. For a long-term cryogenic system storage, you want to do as little mixing as possible, but for a shorter OTV mission you may want to vigorously stir the liquid to eliminate vapor formation at the hot spots that will certainly exist on spacecraft with very little insulation.

I think I agree on the issue of the desirability of intermittent mixing. Boeing has been doing some ground-based testing on mixing, and, in One-G, the mixing forces that you need to overcome buoyancy are rather strong. I think

Low-G experimentation is clearly needed just for the study of the mixing phenomena in addition to identifying what the stratification problem is in the first place. Also, I wonder whether the wall-mounted heat exchangers can really eliminate all the hot spots?

I don't think you can. General Dynamics is considering the use of local heat traps around the tank attach points to eliminate some of the hot spots. In so doing, of course, the requirement for mixing for a long-term storage application will be reduced. However, the design approach for that system would be significantly different than for a vehicle like an OTV.

If for some reason you incorrectly size your TVS heat exchangers for a particular application, you may get more heat into the tank than you've anticipated. If your heat exchanger is located external to the tank on a vapor-cooled shield, the ability to control the tank pressure is probably not going to be there. You need some sort of intimate thermal contact between the heat exchanger and the fluid in the tank.

General Dynamics system concepts do include mixers in the tanks, but we just want to use them as little as possible. We will have to find out, through an orbital test, just how much mixing is required.

One thing I haven't heard discussed at all is the liquid mixing that would result from drag make-up propulsion or attitude control propulsion. Rocket firings will provide impulses to the tank which will cause the liquid to move around in the tank. Possibly you'll get enough liquid motion to meet most of your mixing requirements.

You're going to need to develop analytical models which would probably include numerical techniques. Eventually, you can employ your Low-G data to verify the models.

Along the line of analytical model development, one thing we've run into at Washington University is that there's very little data available if you are looking for details. Most of the experimental work has been driven by specific questions; how fast does the pressure go up in a specific tank, for example. If we're going to develop valid analytical models, we're going to need to be able to predict the details like flow fields and temperature gradients. I think there's a real need to experimentally examine those details not only in One-G, but also Low-G, so particular emphasis needs to be placed on instrumentation selection and placement during the experiment design. Also, in terms of available data, people should understand that mixing can occur in Zero-G. There are effects that are secondary on earth that may cause mixing in Zero-G. They could become dominant, but we won't know that without a test. Additionally, there's a limited amount of qualitative data that indicates that things like turbulence are effected by the microgravity environment. Consequently, One-G testing will provide little insight into the expected Zero-G experimental results.

If you're going to do meaningful tests in orbit, you're going to have to be very exact in identifying the kind of heat leaks you have. It's easy to design a mixer that would destratify anything, but you're not going to learn anything from your experiment unless you know what the input to the system is. Also, an analytical model is not going to be any better than the input you give it.

That's a function of how you design the experiment. For example, you could put a known hot spot or heat leak at one place and the same thing at another place and then look at the interaction between the two.

Thus far we have been discussing mixing as it relates to tank pressure control in response to thermal input. What about other situations where mixing may be required?

Pressure controlled during filling is also important, but it's a transient problem because the conditions in the tank are expected to change. Mixing will be required to promote vapor condensation so that the pressure will not build up too rapidly as the ullage is compressed. However, the controlling processes are difficult to predict analytically, prompting the question, how much mixing is required in order to get the kind of pressure control you want? You're going to have to do some experimentation.

Is it known how much stratification or temperature variation you can withstand? Is it one degree, two degrees, or ten degrees?

It's a question of the resulting pressure in the tank; because the pressure will be uniform throughout the tank, the maximum pressure will be dictated by the region of the tank wall that sees the highest temperature.

I understand, but what is the allowable temperature variation?

It depends on the application. For the depot tank, you can probably tolerate fairly large temperature gradients, because it's not a weight-driven system and it can thus have a relatively high operating pressure.

An OTV, which is a weight-critical system, is going to need fairly good pressure control with a fairly narrow variation in temperature throughout the tank.

What would happen in a tank with no mechanical mixing?

Nobody knows.

There are many secondary effects that could influence the temperature stratification, but we don't know how important they are because they haven't been modeled very well and nobody's done any good experimentation.

I think the only real experience we have is on a system level; for example, the performance of the Apollo supercritical cryogen storage systems. When the decision was made to take the fans out of those systems, the performance was not a great deal different than it was before, but the tanks weren't well instrumented, so nobody understands why the pressure histories were nearly unaffected. We just know there must be some secondary effects that provide mixing.

It seems to me there are a lot of questions about this whole issue; are they going to be answered as part of this program? Is a whole new effort to look at stratification under different gravity conditions required, or are we just going to try to correlate what data we've got at this point in time and use that to establish what a jet mixer has to do?

I think we need a lot of experimentation with a very carefully instrumented apparatus.

I think what I'm hearing is that this technology area should definitely be part of our planned flight experiments.

Can gas can size experiments be employed?

I'm not saying how to do it, but that it should definitely be part of the program.

How Lewis is going to accomplish the program is the next step in the planning exercise; we really didn't want to get into that today, because I think the discussion could go on forever.

Is Lewis' microgravity science experiments program addressing some of these issues?

Yes.

I would like to point out that on IRAS we did have what appeared to be a special effect on the stratification when we got some kind of a rollover. This was with normal helium after it had been sitting for some time. We got a very sharp change in the pressure, and the vent flow rates changed by a factor of three or four or even ten. The flow rates would go up three or four times normal and then drop almost to zero. This apparently had to do with the establishment of stratification followed by rollover.

Was the phenomena correlated with things like attitude control system firings?

No, no, this was during the ground testing.

Because we were dealing with super fluid helium on-orbit, we never saw any stratification effects at all. During the ground testing with normal helium, we observed really major changes in the pressure; it was enough to be of considerable concern. So, you want to think carefully about allowing stratification that may cause pressure surges and pressure changes. It's important to control the stratification.

Taking the fans out of the Apollo tanks did have an enormous effect on stratification.

However, the operation of the Apollo was generally in a barbecue roll mode so there was a Low-G level at all times.

The Shuttle PRSA system has the same problem due to reaction control system firings and the astronauts moving around. We have seen large pressure drops, and that would be a significant problem for something like an OTV. Operationally, if you set-up significant stratification and then get mixing as a result of propellant settling, the tank pressure would drop and your engine feed system net positive suction head would disappear.

### C. Refrigeration/Liquefaction System

#### Benefit:

- Minimize or eliminate cryogenic storage system boil-off losses
- Enable on-orbit production of cryogenic propellant from water

#### Issues:

- System complexity, reliability, and efficiency (input power and heat rejection)
- Loss of refrigerator working fluid
- Integration with and impact on the rest of the thermal control systems
- Quantifiable system level (including logistics) benefit

#### Experimental Approach:

- Ground test of integrated system after component design and test

#### Current Program:

- GSFC is supporting work on Sterling, turbo, magnetic, and open cycle coolers
- ARC is working on pulse tube and magnetic coolers
- AFWAL program is supporting VM, turbo, R<sup>3</sup>, and magnetic sorption concepts
- JPL is working on chemisorption and adsorption cooler concepts and bidirectional Joule-Thomson valves

### Discussion

I know at one time there was concern about loss of the working fluid from mechanical refrigeration systems; are those problems essentially considered to have been solved?

The working fluid loss was a result of the high vacuum environment. Do you do your life testing in a vacuum environment?

No, we don't. GSFC's cooler is not tested in a vacuum environment.

Does the concern still exist?

A complete closed system has not really been demonstrated for a long

period of time. Part of the concept the DOD is developing includes a little make up bottle for fluid replenishment.

So, fluid loss still is an issue then?

Yes, perhaps a secondary issue compared to the life of the refrigerator itself, but it's something that should be addressed eventually.

You would not have to go to space to do that though.

That's right.

The feeling is that the only justification for taking a refrigeration unit into space would be if it's part of an overall systems level demonstration.

If we're going to recommend inclusion of a refrigeration unit on a large-scale ground system demo, then flight testing might not be required.

The other issue is how a refrigeration system may impact the performance of other systems. You've got to demonstrate the performance of a complete integrated cryogen storage system.

Absolutely. One of the concerns that Lewis has with flying something like that on our experiment is the power requirements associated with it.

I was trying to express that concern by indicating the low efficiency of cryogenic refrigerators. The low efficiency shows up in the size of the radiator because you have to get rid of all the waste heat.

It hits you on both ends; it concerns both the power requirement and the radiator.

After recalling the presentations that we heard yesterday, is that the sum of the work that's being supported in this technology area?

As far as I know.

JPL is also working on a wide range of sorption systems.

Ball is doing some work as part of their IRAD program.

#### **D. Radiator Performance**

##### Benefit:

- Rejection of waste heat from refrigeration/liquefaction system

##### Issues:

- Performance degradation due to space environment

- Two-phase, Low-G heat transfer

#### Experimental Approach:

- Ground-based facilities can be employed to simulate space environment
- Shuttle mid-deck or Spacelab experiments will address two-phase heat transfer

#### Current Program:

- Space Station power system development activity is providing adequate support for this technology

#### Discussion

The facility you saw yesterday is being used to determine the degradation of radiator materials in the space environment due to atomic oxygen. I guess my impression is that at least that particular aspect of this technical issue is being well addressed.

There is a lot of interest in using two-phase heat transfer for radiators or thermal control loops in space; but there is still a lot of uncertainty about how those things are going to perform in the low-gravity environment.

We've been looking at things like vapor-cooled shields and, the thinking there is that the tube sizes are going to be so small that you're not going to notice any gravitational effects.

When you start talking about large thermal control systems, there may be gravitational effects on the fluid flow regimes and the heat transfer coefficients.

I still think you'll have pretty high Reynolds numbers.

Unless you have a need for a cryogenic radiator, I think the radiator requirements for the heat rejection from refrigerators and avionics, for example, is being taken care of by the thermal control people at JSC.

They certainly have a program that will meet NASA's needs.

The DOD is working on a liquid-droplet radiator concept. They're driven by different considerations, because they want something that not only has high efficiency but is also compact and, thus, less visible.

There was one comment that was made that at high Reynolds numbers you're not going to see much difference due to the gravitational environment. I understand what was said, but I'm not totally sure of it, because for two-phase flow boiling and condensation, you're going to see different flow regimes and heat-transfer phenomena in-space than you see on earth, and the whole effect could be different.



I agree with that. Lewis is supporting some work at the University of Michigan in that area. Dick Vernon is the grant manager.

Yes, we're looking at boiling at very low velocity. That is from zero velocity up to Reynolds numbers on the order of 5,000.

Is the plan to eventually fabricate a Shuttle experiment to do work like that?

Yes.

I've already run forced convected boiling and condensation tests using the KC-135. We have some data, but it has not been published yet; it will probably be published by the end of the year.

We probably should consider the KC-135 tests to be a stepping stone to eventual in-space experimentation.

When you talk about radiators, you should also include the external surfaces of tanks, since they act as radiators also and you want to keep them as cool as possible.

That was the reason that we took you on a tour of our atomic oxygen facility, because the experimental approach used there to study radiator materials can be applied to materials for thermal-protection systems on cryogenic tankage.

### III. LIQUID SUPPLY/PRESSURIZATION SYSTEM PERFORMANCE

#### A. Helium/Autogenous Pressurization

##### Benefit:

- Enables single-phase liquid transfer by providing required pressure differential and liquid subcooling

##### Issues:

- Effect of hydrogen para/ortho composition on autogenous pressurant requirements
- Influence of low-gravity environment on interfacial heat and mass transfer process
- Pressurant injection technique
- Effect of pressurant temperature

##### Experimental Approach:

- Perform ground-based testing over wide range of experimental variables with selected test conditions to be explored on COLD-SAT

##### Current Program:

- None. Existing data base for rockets not applicable due to high liquid flow rates and acceleration environment

#### Discussion

When we talk about autogenous pressurization systems, the thing that comes to mind is a rocket engine in which you bleed hydrogen off the system and use it to pressurize the tank. However, we've been talking about taking the boil-off gases from the depot, compressing them, storing the gas in an accumulator, and then using them later in the pressurization systems. I, at least until recently, didn't recognize a problem that exists with this concept. By storing hydrogen gas for a reasonable amount of time, it is going to convert to the ortho configuration. If we then use that ortho-hydrogen to pressurize a tank, without intentionally reconvert it in the process, it's going to convert to para-hydrogen after we've accomplished our liquid transfer, and, thus, add heat to the storage system, increasing the boil-off.

A dooms-day analysis.

I don't think there are any gravitational effects, but, from an experimental point of view, we didn't recognize what we were doing in our early planning for the Cryogenic Fluid Management Flight Experiment (CFMFE). We were going to

store hydrogen gas in high-pressure bottles, and we were telling people we were simulating autogenous pressurization without recognizing the fact that we would have ortho, not para, hydrogen pressurant.

I'm not sure how the system should work; I think you would want to use a catalyst in the pressurization system to promote the ortho-to-para conversion as you pressurize the tank.

The alternative is to extract liquid from the tank and vaporize it with a non-catalytic heat exchanger prior to injection into the tank as pressurant.

Setting aside the para to ortho conversion effect, there is another effect that can cause significant collapse of that ullage during tanking operations. You want to minimize the amount of super heat in the pressurant gas used, otherwise you're going to be creating additional boil-off.

Superheated pressurant gas also increases the probability of large transients in the tank pressure.

The selected pressurization technique is also complicated by the fact that you might tank an OTV and then be required to detank the vehicle due to a scrubbed mission. Pressurizing the vehicle, to a high level, to accomplish back transfer imposes a severe weight penalty on the OTV tankage.

Our original thinking in terms of the justification for doing this work in space was that the interface heat and mass transfer could not be simulated on the ground. Not only do you have a gravitational effect on the amount of surface area exposed to the pressurant, but also the actual heat and mass interchange between the pressurant and the liquid was going to be effected by the gravitational environment.

I agree and the liquid mixing phenomena will also effect pressurization to some extent.

Is there a Strawman schedule for refueling, tanking or detanking? Do you have a figure in mind as to how long pressurant may have to be stored?

It's very sketchy. I guess it's usually expressed in terms of a certain number of OTV missions per year.

For the depot studies performed by General Dynamics, we had a typical OTV mission every 30 days with a resupply of propellants from the ground every 90 days, but, those were somewhat arbitrary ground rules to use.

We looked at tanking an OTV, which involves about 50,000 pounds of propellants in two to four hours.

That was something Lewis worked up several years ago, in conjunction with some of the people at JSC, which was based primarily on a gut feeling that you ought to try to do an OTV tanking within an eight-hour shift.

I think that is one of the more ambitious OTV mission models...a flight once a month?

MSFC is in the midst of creating a new Revision 10, mission model. The new model is nominally less ambitious than the Revision 8 model that was used for the General Dynamics study.

But, there's no regularity to OTV flight frequency; once a month is just an average.

That is right; we don't have set missions established.

So, you can't really include a flight schedule in your plans for dealing with pressurant, because OTV missions could be two days apart or two months apart.

That says if you're going to try to collect the boil-off to use as pressurant, what happens is you need a large accumulator to allow for the uncertainty in the times between OTV missions.

From a safety stand point, we didn't like those big, high-pressure accumulators at all. There was enough stored energy in those things to blow the Space Station into little pieces.

Have you looked at metal hydrides which are not only very heavy, but also very compact?

The way metal hydrides look attractive to us is to use them as compressors. But, in terms of a permanent material to store the hydrogen in, they're just too heavy. Everything we're seeing now about the way the Space Station would like to operate indicates we're probably going to end up with a co-orbiting depot or a tethered depot.

MSFC's current thoughts on an OTV servicing facility are that it would be a co-orbiting platform in the vicinity of the Space Station.

Does your depot concept include bays for payload and vehicle servicing, or would it be just a fueling station?

That's still up in the air. I think possibly the total package has a little more support, but you could do all your payload operations at the Space Station and then transport the assembled OTV and spacecraft to the depot with an OMV.

The problem with that is, if you have manned operations at the depot, then you need to transport men from the Space Station to the depot too.

That's true. But, I think right now the combined servicing kind of depot has a little more support at MSFC. The decision will be influenced by both contamination and safety concerns. I think they're driving us to the conclusion that the depot should be close to the Space Station, but not too close.

We've recently heard of a controlled vent rule for systems surrounding the Space Station, but we don't have any limits established; there are no numbers.

The other consideration that tends to drive the decision the other way is that there are lots of good uses for the hydrogen and the oxygen boil-off gases

if you can convince the people responsible for the propulsion, power, and life support systems to use the depot boil-off.

Then they'd like to have the depot attached to the Space Station.

The propulsion system is currently planning to use electrolysis of water as a means to get rid of waste water and provide propellants for hydrogen/oxygen thrusters.

It will also employ resisto-jets, working on the waste gases from the materials labs, to provide quite a bit of the reboost requirement.

That's the current program direction, but we still end up hauling a significant amount of water to the station.

If liquid hydrogen and oxygen are stored on the station, could the boil-off be combined to provide water?

No, the relative boil-off rates are too far from stoichiometric.

One of the other concerns associated with a depot located on the station is the large mass and resulting center of gravity (CG) problem. The depot mass is pretty significant compared to the weight of the Space Station, and by attaching that large mass, you shift the CG and also change the microgravity environment of the science labs. As you fill and drain the tanks, you're continuously shifting the CG and changing the microgravity environment.

## **B. Mechanical Pumps and/or Compressors**

### Benefit:

- Enables single phase liquid transfer by providing required pressure differential and liquid subcooling

### Issues:

- System complexity, reliability, and efficiency (minimize heat addition to transferred fluid)
- Pressurization required to preclude pump cavitation
- Pump/liquid acquisition device interactions

### Experimental Approach:

- Component testing followed by integration with ground-based transfer system experiment

### Current Programs:

- Lewis has recently completed in-house testing of vane pumps and is supporting contractual development of centrifugal pumps at Rocketdyne
- ARC/NBS are testing centrifugal liquid helium pumps with and without liquid feed via screen acquisition devices
- ARC is supporting the development of a high-speed liquid helium pump at Creare
- DOE and the Fermi Labs have tested an immersed pump and drive systems for more than 10,000 hours in both helium and hydrogen
- JSC/Creare/Astronautics are jointly involved in a program to develop magnetic couplings which would allow a pump drive to be external to the tank

### Discussion

John Schuster's presentation showed the problems associated with the use of an autogenous pressurization system and what that does to the subsequent boil-off from a liquid hydrogen storage system. A possible way to get around the problem is to use mechanical pumps as a way of providing the pressure differential required for liquid transfers. Unfortunately, to my knowledge, the agency is not currently supporting any work in this area.

ARC is developing helium pumps. Possibly the technology could also be used for hydrogen applications.

There is centrifugal pump work being done at NBS and there was also some work done here at Lewis on small centrifugal pumps for the low-thrust chemical propulsion application. I don't think anybody's looked at these pumps to see if they are in the right flow range or the right pressure head for the hydrogen refueling application.

The NBS pump is for low-pressure head. The Department of Energy also has a centrifugal pump, which I think they use to deliver hydrogen, which develops a lot more head than the one that NBS has been using.

We may only need about five psi pressure differential.

You don't need much head, but you still want something that's pretty efficient.

The inefficiency of the pump is going to show up in the enthalpy of the transferred liquid, and that tends to increase the pressure or reduce the fill level of the receiver tank. The existing data base is for rocket engines. Some LH<sub>2</sub> pump work, that may approach our needs, was done as part of the low-thrust chemical propulsion system technology program.

Another Ames supported activity, which we didn't talk about the other day, is a helium pump being developed at Creare as part of the small business program. This pump may be more efficient than the others we have discussed.

My thinking is that pumps should be a candidate for inclusion in a ground-test program, but I can't see any reason why you would fly them. You could use helium pressurization as a way to simulate the performance of a pump.

Not if we're going to transfer several times back and forth between tanks.

I think pumps ought to be part of a ground systems demonstration.

There might be problems with the integration of pumps with fluid-acquisitions devices. You could create enough pressure differential with a pump that you cause cavitation or ingest vapor into the liquid acquisition device (LAD). It should be part of an overall test strategy to purposely exercise your pump to create upset conditions to see how the system responds.

One thing that you have to look at in your evaluation of pumped transfer is the reduction, not elimination, of pressurization system requirements. You only need to pressurize the tank to create the net positive suction head required by the pump.

You might be talking about tenths of a pound of pressurization versus ten pounds of pressurization. This could be a more significant system impact than the efficiency of the pump.

The concern I was trying to express is that when you're trying to load a tank with the no-vent fill technique, you don't want to add enthalpy to the liquid either, because that'll effect the final state achieved in the receiver tank. It's not like a ground system where your tank is continuously vented to get rid of the energy. I personally don't have a feel for whether or not the heat added due to pump inefficiency is significant.

#### IV. LIQUID SUPPLY/ACQUISITION

##### A. Fine Mesh Screen Liquid Acquisition Devices (LAD)

###### Benefit:

- Provides single-phase liquid supply enabling on-orbit transfer of cryogens

###### Issues:

- Expulsion efficiency (residuals)
- Impact of heat addition
- Contamination or degradation, due to repeated cold shocks

###### Experimental Approach:

- COLD-SAT will provide data to establish LAD expulsion efficiency and sensitivity to heat addition
- Ground-based testing can address contamination and degradation issues

###### Current Program:

- Martin Marietta has recently designed, fabricated, and delivered to NBS and GSFC liquid helium LAD's which when coupled with pumps have reduced the pumps sensitivity to net positive suction head

#### Discussion

Even though LADs have flown with non-cryogens, those systems were never taken to depletion, so that we have never confirmed that our predictions for the expulsion efficiencies are right. What's the absolute limit of the amount of liquid you could get out of a tank which contains a screen device? For the cryogenic systems, there's a concern about the effect of heat addition to the system. My own feeling is that we're probably going to have systems that are so well insulated, even for the tanker type application which is probably about the highest heat flux that we envision, that the heat addition will have minimal impact on LAD performance.

In that regard, I think the COLD-SAT should provide a system demonstration; that demonstration should show that LAD's would perform under a relatively high heat flux without detectable degradation. An additional LAD concern is that screen devices make good filters and so with time they will tend to accumulate any contamination that you've got in your system. This is a particular concern for a system like the depot which you're going to be constantly resupplying. Any contamination that you carry up in your transport



vehicle is going to tend to accumulate in the acquisition device in the depot. I'm not sure how we should be addressing this issue.

On the Shuttle, we fill through the screens into the OMS tanks, so if you accumulate particulates they are flushed back out through the engines.

How are you going to load the depot?

I would think the same way, so the Shuttle scenario is very applicable, in that you are generating a lot of experience right now.

Martin Marietta just disassembled a couple of RCS tanks that were removed from Shuttle service. They look just like they were brand new as far as the screen condition is concerned.

The heat addition issue was sort of passed over by saying the tanks are going to be well insulated. Will that be true for all tanks?

Years ago Lewis supported some work at McDonald-Douglas, where we tried to dry out screen materials in a liquid hydrogen environment, and it was nearly impossible.

We tested at some tremendous heat fluxes. If you had those kind of heat fluxes on a tank, you wouldn't have hydrogen in it for more than a few minutes.

I think it's safe to assume that you can't dry out a screen if it's in contact with the liquid, but the exit of the LAD is going to be near one of the tank penetrations, and you could get some bubble formation there that might migrate up channel. Then you could have a place where the channel's exposed to vapor on both sides of the screen and you might get screen dry out there. You certainly want to avoid a design that would have the possibility of actually generating vapor internal to the devices. I think that's just smart design; I'm not sure there's any new technology required.

Combining a thermodynamic vent heat exchanger and your LAD into an integrated system concept should eliminate the problem.

That approach was being used by Martin Marietta on the CFMFE design. Somehow you actively cool the penetrations so that you'll preclude any vapor generation.

How about screen materials that are compatible with liquid oxygen...is that a problem? Do you use stainless steel or does that create fabrication problems?

All the screen materials we currently use are stainless steel.

We may want to develop aluminum screens for hydrogen use just to save weight.

They have just started making them.

The problem is that you can't really get the aluminum wires fine enough to create the fine mesh screens.

## **B. Fluid Settling and Outflow via Low-Level or Impulsive Acceleration**

### Benefit:

- Provides single phase liquid supply enabling on-orbit transfer of cryogenics

### Issues:

- Minimize Depot propulsion requirements
- Establish reasonable depot/spacecraft operating scenario

### Experimental Approach:

- In-space experimentation required; time and size constraints preclude use of drop towers

### Current Programs:

- Lewis is supporting numerical modeling work at Los Alamos National Laboratory and Washington University

## Discussion

Low-G fluid transfer is an area that was explored here at Lewis in drop tower experiments years ago. If we go to a tethered depot or possibly a spinning depot concept, we're still going to be talking about a very low-gravity environment and the fluid management problems don't go away, they're just different.

Previously, we were constrained by the Shuttle environment and we didn't feel we could do experimentation in this area because we were a Shuttle-attached payload. Now we're talking about a free flying spacecraft where we can control the environment either by spinning the spacecraft or selective thruster firings. I think there is an opportunity to expand our experimental objectives.

Tests in the KC-135 could probably provide some information.

Certainly, if the propellant depot is a free flying platform, you may be able to use some thrust or spinning to settle the propellants.

I wonder if there's a positive trade off to doing that though? I'm not convinced. It might be better just to have an acquisition device so that you don't need to be concerned about the gravitational environment or any low-level adverse accelerations.

When you talk about tanking an OTV that is mated to the propellant depot, do you want to have to initiate thrust?

Probably not.

We may want to look at Low-G fluid transfer for certain applications, but I think when we consider filling an OTV from a depot, it will be under microgravity conditions.

If the OTV servicing facility is attached to the Space Station by a tether in a low-gravity environment, then Low-G transfer is a possibility.

Currently, based on the work that's been done, there appears to be two camps; one says tether and the other says not to tether. MSFC really hasn't found too many instances where tethers are desirable.

Tethering small masses may make some sense, or it may make sense where the G level produced isn't going to create problems elsewhere. However, the depot is such a huge mass, on the same order of mass as the Space Station, that the tethered depot concept doesn't look promising.

A tethered depot certainly does create a lot of other problems, including operational problems associated with docking resupply vehicles and transporting hardware between the depot and Space Station.

The most desirable depot propellant management approach probably is to have a very low gravity environment and employ some sort of an acquisition device.

That way you're assured of success.

One of the issues for the OTV application is the trade off involving partial LAD's in the OTV versus propellant settling by the thrust system. Thus far, we've talked about total acquisition type LAD's for the depot, but they could be a consideration for the OTV itself; that is for the abort condition to enable emptying the tanks and saving propellant. That consideration might push you to wanting a depot that has a Low-G environment, so that you could back transfer from the OTV to the depot as well without having to put a total acquisition device in the OTV.

I hadn't thought of that, but that's another approach.

That way, you don't have to carry the weight penalty of a total LAD with the OTV on every mission when you don't need it.

That is an important consideration because the OTV's will be weight critical.

Help me understand some of the discussions; is the purpose of your flight experiment only to get the technologies for the depot and the OTV, or are you also considering experiments that will be helpful for other applications in the future?

I think we would like to believe that this is a general technology program, but it's clear that it's focused on two key applications, the orbital depot and OTV.

I would like to make a comment on ground-based test facilities. The KC-135 is very good for some problems and does provide a lot of things that drop

towers cannot, but there is a danger in relying too much on the KC-135 for the filling of tanks. As you will recall in the movie we saw yesterday, the initial conditions are far from ideal and will likely effect the experimental results.

That's one of the reasons why we at Lewis think the drop towers are probably better; even though they don't provide as long a Low-G environment as the KC-135, you have a lot better control over the initial conditions.

For this particular case, Low-G inflow and outflow, there is a fairly extensive drop tower-obtained data base that has been used to verify numerical modelling techniques. I think we've probably reached the limit of what we can do in drop towers.

You could start this kind of experimentation with the supply tank completely full.

That would possibly be a way to overcome the limitation associated with the KC-135 initial conditions.

In an attempt to provide general technology, I know resolution of each of these technology issues will involve a certain cost, including the experiments. I'd suggest that even though this technology may not have direct application to the depot, it may not be a weight or size problem if included in the flight experiment, and would provide information that we can't get elsewhere.

The major concern for the flight experiment is that this technology might end up driving the spacecraft attitude control system requirements such as thruster size and propellant usage, but if it does not, I think you're right, and it will be a small price to pay to include it.

Is it clear that a screen-type liquid acquisition device is going to be adequate to provide the flow rates that are required for filling an OTV?

Yes, but I think a more critical problem is the issue of back-filling the depot from the OTV, in the event of an OTV mission abort, without having a significant weight penalty on the OTV.

I'd like to make the point that, during the flight experimentation, we may want to impose a known acceleration on the system for other reasons; we might want to use point-level sensors to establish tank fill levels, for example.

I think what I'm hearing is that this technology issue would be a nice thing to include in the flight experimentation, but it's tough to justify based on the identified key applications.

Consequently, it should be accommodated if that can be accomplished without significant impact on our program.

I agree; unless we consider that part of the scenario which involves putting fluid into an OTV and then possibly aborting the mission and having to get the propellant back out. I haven't heard any good suggestions on how we would do that other than putting some sort of a Partial-G environment on the system. The only alternative would be an acquisition device and the resulting undesirable penalty in weight.

One other thought that might be pertinent in this area is that since we're talking about the supply system and tanks in general, some type of a visual system inside the tanks for observing the fluid motion might be appropriate. Should we possibly consider developing something in that arena like fiber optics?

We have fiber optics in the COBE dewars going into the instruments from the outside.

Does the instrument significantly contribute to the heat leak to the system?

The fiber optics have very low thermal conductance.

## V. LIQUID TRANSFER

### A. Transfer Line Chillydown (Forced Convection Boiling)

#### Benefit:

- Enable single phase liquid transfer

#### Issues:

- Minimize cryogen usage
- Quantify effect of acceleration environment on two-phase flow regimes, heat transfer rates, and pressure drop

#### Experimental Approach:

- Basic research in-space experiments to establish flow regimes
- COLD-SAT to provide data on heat transfer rates and pressure drop

#### Current Program:

- LeRC is supporting experiment definition studies for flight on the Shuttle and analytical modeling efforts at the University of Michigan
- Experimental and analytical studies, at the University of Houston, to determine the effect of the gravitational environment on two-phase flow regimes and pressure drops, are also being funded by LeRC

### Discussion

For transfer line chillydown, my thinking is in Low-G we may have a difference in flow regimes, but we probably won't have a significant difference in the heat transfer rates. From an engineering point of view, it's really the heat transfer rates, the pressure drop, and the amount of cryogen usage that's of interest. I understand that there's a scientific interest in knowing what's going on inside the tube, but from an engineering point of view, I'm not sure that that's all that important.

I believe I disagree. There definitely will be differences in pressure drop; there could be as much as a 50 percent increase in pressure drop in Low-G as compared to normal gravity conditions.

The amount of liquid you lose in cooling down the system is so small compared to the total amount of cryogen to be transferred that the problem is insignificant; that is at least from an engineering point of view.

The question really is whether or not a liquid hydrogen transfer system is a good place to get this kind of experimental data.

I think you could design better experiments for studying two-phase flow.

Okay, that was the approach we had in mind. The CRYO-SAT could be used to observe the differences in pressure drops and heat transfer rates, but we would not try to establish what the actual flow regimes were.

Right, a cryogenic flight experiment is really not an appropriate place to try and do that.

## **B. Thermal Conditioning of Liquid Outflow**

### Benefit:

- Enables single phase liquid transfer to spacecraft tankage designed to operate at modest pressure levels

### Issue:

- Effect of low-gravity environment on thermodynamic vent system heat exchanger performance

### Experimental Approach:

- Design dual purpose thermodynamic vent system providing pressure control and liquid thermal conditioning, for testing both on the ground and in space on the COLD-SAT

### Current Program:

- In-house design effort at Lewis

## Discussion

One of the advantages of using helium as a pressurant is that you maintain the thermodynamic condition of the liquid at the partial pressure of the hydrogen, so that's a way of maintaining the desired liquid subcooling which is an advantage when you're trying to transfer cryogens. In addition, we were planning to explore the idea of using a thermodynamic vent system as a cooling technique to provide liquid subcooling.

Was the idea to vent through the TVS during transfer?

Yes.

Is that to keep the tank temperature or pressure down while you're filling?

The latest CFMFE supply tank concept had one of the thermodynamic vent systems integrated with the acquisition device. This approach provides cooling for the major penetration, precluding vapor generation in the outflow line, and, during the transfer operation, it could also be a means of cooling the liquid to provide additional subcooling. I don't think there's any gravitational effects associated with the concept, and performance testing can be conducted on the ground.

I think the concept could be employed on OTV's as well to meet your engine Net Positive Suction Pressure (NPSP) requirements.

This was an alternative that was looked at for an advance Centaur design years ago; it was called a subcooler and it was considered as an alternative to a boost pump for the RL-10 engine.

When you're using a TVS as both a pressure control device and as a subcooler, isn't its cooling capacity determined by the cooling rate required during transfer as opposed to during normal venting? Aren't their orders of magnitude difference in the required cooling rates?

I guess there probably would be.

How much do you want to subcool? I think it's fairly obvious that you would want to subcool enough to at least preclude any vaporization in the transfer line, but anything more than that may not be of value.

Okay, so if you're just providing an equivalent NPSP, to overcome line losses, the requirements may not be too different.

In the helium transfer system we have two thermodynamic vent systems. One is operated during stand-by modes, and one is operated when the centrifugal pump is on. However, the pump can run at a negative NPSP, so we don't need to have much subcooling, and we don't need to have the liquid pressurized much.

How critical is it during the tank refill operation that you don't get any bubbles in the transfer line?

The issue is that if the receiver tank you're trying to fill has a screen acquisition device, you may trap vapor inside that device during the filling operation. I would like to avoid that problem if possible.

### **C. Receiver Tank Chillover**

#### **Benefit:**

- Desired receiver tank pressure, following no-vent fill, is controlled by the temperature to which the tank is chilled prior to initiating the transfer operation



Issues:

- Minimize cryogen usage /
- Liquid injection technique and sequencing
- Effect of acceleration environment on heat transfer rates
- Use of thermodynamic vent system to provide tank chilldown

Experimental Approach:

- Ground-based transfer system testing and in-space experimentation on COLD-SAT

Current Program:

- Analytical model development and precursory experimentation at Lewis

Discussion

One thing that should be added to the chill down issue is the coupled heat exchanger concept. It is much more efficient to consider chilling your receiver tank down by employing a tank-mounted heat exchanger as opposed to the spray systems. It might be worthwhile to look into that approach as an option, because I think the heat transfer and resulting process efficiency will be better for that type of a concept.

**D. Receiver Tank No-Vent Fill and Refill**

Benefit:

- Enables predictable tank filling capability for reusable space-based vehicles and satellites

Issues:

- Effect of acceleration environment on fluid dynamics and heat and mass transfer rates
- Liquid injection technique and sequencing
- Application to supercritical systems

Experimental Approach:

- Ground-based transfer system testing and in-space experimentation on COLD-SAT

### Current Program:

- Analytical model development and precursory experimentation at LeRC
- MSFC-sponsored Space Station Integrated Propulsion and Fluids Systems Study at Martin Marietta is examining resupply options for the nitrogen tankage

### Discussion

An issue that was raised by one of the participants is whether or not we should be considering the resupply of super-critical systems.

My thinking is that if you had a super-critical system that you wanted to resupply, you would do the transfer sub-critically, so that we would address the technology issues in our current plan.

If the super-critical system you are trying to resupply is not empty when your tanker gets there, you may dump a lot of cryogen in the process of getting the tank ready for sub-critical filling. That might not be a very economical operating scenario.

If you resupply the tank super-critically from a super-critical supply system, it would be a lot like the transfer of high-pressure gas.

It becomes just a single-phase fluid transfer.

The transfer system still has to be well insulated. I'm not sure anyone has really looked at the problems associated with super-critical transfers. I think they have assumed that the transfer is performed sub-critically and then the system is repressurized.

Mixing characteristics will be all together different; super-critical fluid mixing is much easier than sub-critical fluid mixing.

Current operational super-critical systems that I'm familiar with, at least the PRSA, are loaded sub-critically and allowed to self-pressurize to the super-critical state. Is there an application for super-critical system resupply technology?

There are some planned DOD spacecraft that will employ super-critical cryogen storage systems.

Is resupply of those systems something the military is considering?

Yes.

How would you physically push enough mass into the receiver tank if it is kept at the high pressure super-critical state?

You need a high-pressure pump.

Or you might need an even higher-pressure supply system.

Receiver tank cooling will probably be required at the same time, because you are going to be creating so much energy in the tank that, without cooling, the tank will reach its pressure limit and still not be very full.

Evidently, supercritical system resupply is primarily a military concern and should not be a part of NASA's program, but that doesn't mean we should forget about it. It also sounds like the problems are unique to a specific system.

There is one other application that is under discussion; that application is the resupply of nitrogen to the Space Station. How nitrogen should be transported has not been determined.

Tank changeout is a possibility.

It is not clear that that is the best way to do it.

Do you plan to use super-critical storage for that application?

We don't know. The trade studies that we will have to do will consider sub-critical liquid transport and on-orbit transfer, as well as super-critical tank changeout.

MSFC has a contract with Martin Marietta to look at the whole Space Station nitrogen system, and this issue is one of the things they are addressing.

One thing you might consider, since you are talking about carrying high-pressure hydrogen on board the spacecraft for pressurization purposes, is to use a super-critical hydrogen tank as a source of pressurant and then you might be able to address both of these issues.

I'd just like to note that the tank mixing issue we covered under the storage heading applies to the tank filling process as well.

Yes, they are very similar. The interface heat and mass transfer phenomena is the key to both processes.

#### **E. Venting of Non-Condensable Pressurant**

##### **Benefit:**

- Enables orbital resupply of spacecraft fluid systems which utilize non-condensable pressurants (i.e., helium)

##### **Issues:**

- Effect of acceleration environment on desire to vent non-condensable gas with minimum loss of liquid cryogen

Experimental Approach:

- Not currently recommended for inclusion in program (see following discussion)

Current Program:

- None

Discussion

What about the problem of gradual accumulation of helium in your orbital storage tanks? When you try to resupply the tanks, you're going to be compressing the helium, and the tank pressure will increase rapidly.

Really, the issue is how you vent the non-condensable gas, because I think it's clear that, if you're accumulating helium, eventually you won't be able to resupply that system.

For the depot, our thinking was that you probably don't want to use helium pressurization; you want to figure out another way to do it. But, for the OTV, it's not clear how you should pressurize the tanks. You might want to use some helium pressurization on the OTV. Have the OTV studies addressed pressurization systems?

I talked with Don Saxton the other day and the only thing that he mentioned is that helium seems to just add another fluid to the resupply scenario thus complicating the operations.

How do you get the engine system started without helium?

They're expecting to use tank head idle with the new engines.

Just by cooling the engine, you generate enough vapor to pressurize the tanks?

The studies really haven't gone into that much detail yet.

It's always been a goal of the advanced technology engine programs to develop an engine that'll start with zero NPSP, but I guess I don't know if they've achieved that goal.

The issue hasn't really played into the OTV studies yet, but I know they are not planning on using helium pressurization.

The question then becomes, if the OTV studies and the depot definition activities are not talking about using helium, do we want to include helium pressurization as a technology requirement?

This part of the original CFMFE experiment was intended to address how much helium you could vent without losing any liquid. Part of our justification for carrying helium on the experiment originally was to provide a fall-back

position if we had problems transferring liquid hydrogen with autogenous pressurization, since we knew we would be able to easily provide sub-cooling with helium pressurization and thus accomplish the transfer. The other reason for carrying helium comes from a safety point of view; on the Shuttle we had to have some way of dumping the hydrogen and safing the system before we came back from orbit.

If we're going to do many fill-and-drain cycles, doesn't the helium pressurization system get quite large?

We planned to take bottled hydrogen too, even though it was not actually an autogenous system. Our objectives were to get as much scientific information comparing helium and hydrogen pressurization systems as we could; however, we always had the fall back position that, at the very least, we want to learn how to operate a cryogenic transfer system.

Make sure that you can get it to work right.

Yes, that was part of the reason for carrying helium. If the autogenous system didn't perform the way we thought it would, we can fall back to the use of the helium system.

Can you still test the LAD, regardless of the choice of pressurant gas?

One of the problems with autogenous pressurization is, as you approach tank depletion, that the saturated liquid layer is ultimately going to end up in your device. With helium pressurization, the liquid is always subcooled, but with autogenous pressurization, it becomes saturated, and you may effect the expulsion efficiency of the acquisition devices.

Our intention with CFMFE was to do multiple transfers without really testing the acquisition device. Then after we accumulated a fair amount of data on the transfer process, we would take the tank to depletion to determine the LAD expulsion efficiency.

You may find that, after you do several transfers, the thing that breaks down your acquisition device is not the fact that you are stressing the screen very much, but the fact that you have saturated liquid that you're trying to transfer.

During the cryogenic bread-board testing at MSFC, we were looking at the problems during hold periods and we were unsuccessful in holding liquid in the start basket when using hydrogen pressurization, but with helium we were able to hold the liquid in the basket.

Was that test tank well enough instrumented so that you could tell whether or not what you observed was a heat transfer effect?

No, really it was not. We're just about to publish our final report on that aspect of the tests.

Getting back to one of the earlier comments...it is not just the complexity of carrying another resupply fluid that is of concern. If there are large

quantities of high-pressure gas required on-orbit, you are going to spend a lot of time resupplying that gas.

That is another reason to avoid helium if we don't need it.

Unless you do some sort of bottle change-out.

You are going to have to carry a lot of bottles.

That is an expensive operation.

From what I am hearing, there is something on the list we ought to think about deleting, and that is the venting of non-condensable gas.

The use of non-condensable pressurants may be undesirable, but I think it is premature to knock it off the technology requirements list. It seems that you are not going to fly your spacecraft for several years, so that gives us time to address the venting of non-condensable gases with small scale shuttle and drop tower experiments or analysis. Later, you may want to incorporate helium venting as a spacecraft experiment, but I don't think you necessarily want to put that in as a firm requirement for your flight experiment right now.

One of the problems that we ran into when we did include helium venting in the CFMFE was finding instrumentation that would allow us to measure the concentration of helium that would be vented. Also, venting of non-condensable gases was not one of our high-priority technology items. For those reasons, we weren't all that enthusiastic about including it as an experimental objective, but we welcome any suggested measurement techniques.

I wasn't saying that it should be incorporated into the flight experiment, but it seems it would be premature to eliminate non-condensable gas venting as a technological issue.

#### **F. Low-Gravity Vented Fill of Receiver Tank**

##### Benefit:

- Predictable tank filling capability for resupply of space-based vehicles and satellites

##### Issues:

- Effect of acceleration environment on allowable tank filling rate (minimize liquid loss)

##### Experimental Approach:

- Testing performed on COLD-SAT

### Current Program:

- Numerical modeling capability being developed at LeRC

### Discussion

This technology requirement is a companion to the low-gravity draining that we were discussing earlier. If there is a possibility of using tethers or rotating systems, then there is also the possibility that you can use the Low-G environment to control liquid positioning in the receiver tank and allow tank venting during filling. Recalling what we said before...if we can do this without significant impact on the spacecraft design, then it would be a nice thing to include.

Right, it would give us more data.

Since we eliminated the venting of non-condensables as a technology requirement, do we know how to vent the vapor from an autogenous system?

That is just as hard; it doesn't matter what it is.

You could recondense the gas back into liquid. If you want to condition the receiver tank prior to a transfer, you have to drop the pressure somehow.

But, you can reduce tank pressure with a condensable by providing cooling. I don't think we ever figured out a way of getting rid of the non-condensables that we are comfortable with.

Can it be done without dumping liquid along with the pressurant?

Right, that's the question.

For the storable liquid tankage, one advantage of putting vanes on the walls is that the liquid becomes well bound, thus providing access to the gas in the center of the tank. Alternately, some other vane devices hold the liquid in the aft end of the tank. Those approaches are being looked at experimentally at McDonnell Douglas.

I think the problem is that, for the applications we are looking at, we are dealing with much bigger systems, and the weight penalties for vaned devices would be prohibitive.

### **G. Liquid Acquisition Device Fill and Refill**

#### Benefit:

- Enables subsequent single-phase liquid outflow

Issues:

- Venting or condensation of trapped gas (effect of low-acceleration environment during resupply operations; start basket filling characteristics during vehicle engine firings)

Experimental Approach:

- In-space verification of design concepts on COLD-SAT

Current Program:

- None

Discussion

With respect to the liquid acquisition devices, are you going to select just one and test it, or are you going to try to test several concepts?

I think we would have one unique kind of device in the supply tank, and there is still a question about what to put in the other tanks. In the spacecraft concept that was shown to everybody on Tuesday, we are looking at the possibility, at this point in time, of having three tanks. One tank design would be a model depot tank with a channel screen acquisition device; that would be loaded with hydrogen on the ground. The second tank, that we had in the center, was called a tanker tank; its primary purpose is to simulate a tank that would be used to take cryogenics from the ground up into orbit to resupply the depot. The third tank was a scale model of an OTV tank. We have not decided what will be contained in those two middle tanks, yet. We obviously would pick some sort of an acquisition device that would be unique for that specific application. We might want to put something like a start basket in what we call the receiver tank, the scale model of the OTV. The tanker tank would probably have to have some sort of a total communication device, because I think you want to do the transfer under Low-G conditions.

I guess the question is whether you are thinking of the spacecraft as a test bed for working on liquid acquisition devices, or are you looking at acquisition devices as a way to resupply the tanks.

We would like to do both.

The major problem is trying to design an experimental apparatus in which each technology issue can be addressed without compromising the other objectives. We would like to have one receiver tank that is pretty clean, so that we can get some basic data on the chilldown and filling process without having to worry about the effects of internal hardware. We would also like to have a tank that is configured to look like an OTV tank; it could possibly include a start basket and gauging system.

At this point in the spacecraft design, we can say that we expect to have multiple tanks, but we haven't settled on any of the specific configurations.



This technology requirement deals with the issue of how you design an acquisition device so that it can be re-filled in orbit. The concern is whether or not you can refill not only the tank, but also the acquisition device if you completely deplete the storage system. I have seen things written about refillable systems, but I am not sure I understand how they work. As an example, there is a Lockheed spacecraft built for the military which uses Nitrogen Tetroxide and Mono Methyl Hydrazine propellants. The spacecraft employs a channel-type screen acquisition device which breaks down when the satellite engines fire, and then refills under Zero-G conditions.

The Peacekeeper acquisition device breaks down when it is being transported around, and then it refills during launch. Also, many start basket concepts break down and have to be designed to refill.

I was thinking here more in terms of a total communication device like you might have on a depot. People recognize the thermal design advantages of taking the tanks up empty, so that you have to fill the system the first time on-orbit, and you don't want vapor trapped in the acquisition device which would subsequently get into the transfer system. There is also the possibility that the tanks might at times be totally emptied.

Is it really just a design problem?

Yes, I think it is a design problem, but I think it requires verification. It probably also requires Zero-G verification.

I certainly think that addressing this technology issue ought to be a goal of the flight experiment.

How would you instrument the experiment to address this issue?

You can tell if it fills by the way it performs during subsequent outflows. If it doesn't fill, then you don't have instrumentation to tell you what the problem is. You would have to have at least some minimum instrumentation to monitor the condition of the liquid acquisition system.

Do you mean something like liquid vapor sensors?

Yes, that is a possibility.

You could do an experiment with a storable fluid on the Shuttle to try out design concepts and see if they work as expected. A mid-deck experiment with movie pictures could be performed; that's the same way that Martin Marietta did their experimentation.

If you do not have non-condensable gas in the device, you could use cooling to condense the gas.

That's true if you have a thermodynamic vent system heat exchanger coupled to the LAD.

That's right.

Except for a total-communication LAD, you won't have the heat exchanger coupled to the whole device; it is more likely to be just at the outlet. You might be able to collapse the bubbles by pressurization or mixing to remove the heat of condensation from the LAD.

You may find out that the pressure you have to achieve at the end of a tank-filling operation of a previously warm tank will be set by the necessity of getting all the vapor out of the LAD. You may have to overpressure the tank so that you collapse all the bubbles in the LAD. It is an operational procedure you are going to have to address experimentally. The LAD can be designed so that you think it will probably work, but you are going to have to test it to see what happens.

## VI. FLUID HANDLING

### A. Slosh Dynamics and Control

#### Benefit:

- Predictable fluid motion thus allowing the maintenance of acceptable spacecraft attitude control

#### Issues:

- Effect of gravitational environment
- Need for and impact of baffling
- Flow-induced sloshing
- Impact of CG shift resulting from liquid transfer operation

#### Experimental Approach:

- COLD-SAT employed to provide in-space experimental testing

#### Current Program:

- None addressing needs of large-scale systems like the depot and OTV

### Discussion

For the type of flight experiment you are considering with a large supply tank full of liquid which is an integral part of a spacecraft, the slosh of liquid within that supply tank is going to be a major driver in the supply tank and spacecraft attitude control system (ACS) design, because of the desire to point, orient, and rotate the spacecraft in a predictable manner.

One of the issues is whether you are going to have to put baffles in the tanks in order to preclude excessive demands on the attitude control system due to fluid motion.

Are we going to have to put baffles in the OTV?

When we were going to fly CFMFE on the Shuttle, we figured the tail doesn't wag the dog, so liquid sloshing would not be a problem, but now we are definitely talking about much larger tanks; they will be a much bigger percentage of the total system weight.

Are you talking about the sloshing during the launch, or while you are up on orbit?

Anytime.

On-orbit, those fluid motions will be real low-frequency, and they go on forever.

My thinking is that this technology area is definitely a good candidate for inclusion in the flight experiment objectives. However, Lewis is going to need some help to define what it is that ought to be done. These are just some of my ideas. Should at least one tank have baffles? How about flow induced sloshing? This is something that has been observed in some of our drop tower tests, but to my knowledge, there has been very little work done in the area. For some of these large systems, if you induce fluid sloshing as a result of the outflow, it could really perturb the ACS.

Don't you have to have a pretty fast flow rate?

You can excite high-frequency, low-amplitude slosh at relatively low outflow rates. You tend to get higher amplitude and lower frequency at the higher flow rates.

I have a concern that is related to the sloshing problem. The numeric codes that are available are only for analyzing the liquid phase. If you have hot spots in the tank and liquid stratification, liquid sloshing could cause substantial heat and mass transfer, and the numerical codes can't handle that at all.

There is also interaction if you are trying to outflow; that includes the influence of the pressurization system.

We will have to continue to develop the codes that we have.

I don't think the mass change of liquid to vapor resulting from the sloshing motion is going to effect the forces on the tanks.

What I am saying is that if initially there is a local hot spot with a bubble, liquid sloshing and the resulting mixing will lead to pressure collapse, and you are going to get pressure waves traveling through the liquid to the tank.

You will get a pressure collapse from the fluid motion, but I don't think significant forces on the tank wall will result.

Depending on the size of the bubble, it could be significant.

It may make a big bang inside the tank like a water hammer effect, but it will more than likely be a net zero force externally.

But, I think the whole issue is important; the stratification, evaporation, and any other thermal processes taking place inside the tank must be understood and analytically modeled.

In designing a spacecraft, there aren't that many analytical tools available now for predicting fluid/spacecraft interactions. There may be time to use get-away special or hitchhiker experiments, with non-cryogenic fluids, to enhance our analytical capabilities.

It is not completely obvious that you don't need cryogenics, because things can go on at the free surface that may effect the experimentation.

What is being suggested is that this is an area that should involve an all encompassing program possibly starting with mid-deck experiments as precursors to experimentation on the COLD-SAT.

Researchers at the Massachusetts Institute of Technology have designed an experiment they'd like to do.

## **B. Tank Dumping and Inerting**

### Benefit:

- Provide safe cryogenic tankage prior to in-space astronaut proximity operations or system return to earth

### Issues:

- Effect of acceleration environment on fluid expulsion
- Solid cryogen formation, due to low-pressure environment, causing fluid flow interruption
- Quantity of purge gas required

### Experimental Approach:

- COLD-SAT employed to provide in-space experimental testing

### Current Program:

- None

## Discussion

When CFMFE was going to fly on the Shuttle, we had to be able to dump and inert our system in the event of an abort, since we had a liquid hydrogen system. Operationally, we felt that we could accomplish the system-safing required and in the process we would have gotten some scientific information as well. The question is, now that the on-orbit system safing requirement is removed, whether this is still an issue that should be addressed as part of our fluid management technology program?

I have heard some indications that the Shuttle is never going to be used to carry cryogens.

What about ground-based reusable OTV's, or a tanker?

Are those systems ever going to be transferred to orbit by the Shuttle?

A very conservative philosophy exists today, but in ten years that attitude should change.

After ten years in orbit, you may want to replace the depot tankage and bring back down some empty tankage.

I think what we are saying is that dumping and inerting should still be one of our experimental objectives for the flight test.

You have to pressurize those tanks because you can't bring them down evacuated.

Would there be any possibility of fire when you do the dumping?

Not as long as there is no oxidizer.

For an OTV, you would be not only dumping hydrogen tanks, but also oxygen tanks.

Hopefully, that wouldn't happen at the same time.

### **C. Liquid Condensate Collection**

#### **Benefit:**

- Coupled with liquefaction system to provide non-vented cryogen storage system
- Enabling technology for on-orbit propellant production from water

#### **Issues:**

- Liquid-vapor separation under low-gravity conditions

#### **Experimental Approach:**

- Feasible concepts could be evaluated using drop tower or aircraft experimentation

#### **Current Program:**

- Sunstrand, under sub-contract to General Dynamics, developed a phase separator as part of the vent system for the Centaur vehicle that was to fly on the Shuttle

### **Discussion**

In looking at the idea of using mechanical coolers as refrigerators or liquefiers, it would seem that the only Low-G technology issue that I can think

of is how to collect the liquid generated by the liquefier. There may be ways of running the flow through spiral tubes to separate the gas from the liquid.

Isn't this the same problem that exists in two-phase thermal management busses? Technology is being developed for that.

Sunstrand has developed a device for separating liquid and vapor in the Low-G environment. It is one of the elements of the system discussed during their presentation.

Is there anything unique about doing liquid-vapor separation in a cryogenic system?

I can't see any.

The only thing that stands out is that your flow rates will be quite low. You may not want to expend much pressure drop creating high flow velocities that may be required to effect the separation. Some type of capillary collection device might be desirable.

The tube diameters are probably going to be pretty small. Ideas that General Dynamics has looked at include wrapping a coiled tube around the cold finger of the refrigerator and assessing the problem of creating sufficient centrifugal force to assure orientation of the liquid that condenses. I don't think it is a big problem.

If we decide that we really want to have a liquification system; of course, that is still an open issue, maybe some of these concepts could be evaluated in drop tower experiments.

**D. Earth-to-Orbit Transport of Cryogens as Subcooled Liquids or Liquid/Solid Mixture (Slush)**

**Benefit:**

- Eliminate tanker vent losses
- Minimize depot vent losses both for pressure control and liquid thermal conditioning prior to transfer

**Issues:**

- Large-scale production and ground handling capability for slush
- Low vapor pressure safety concerns
- Unique mixing, pressurization, and gaging requirements associated with slush

#### Experimental Approach:

- Ground-based experimentation and pilot plant demonstration of slush production capability

#### Current Program:

- The National Aerospace Plane technology maturation program is supporting a significant effort in this area

#### Discussion

This is a technology area that is suggested for inclusion in the program because of the General Dynamics OTV concept that employs sub-atmospheric pressure tankage.

What I am suggesting is that if low-pressure tankage really looks like it is attractive for some space system, then we have to address the issue of how to resupply that system. It doesn't make a lot of sense to transport normal boiling point hydrogen to orbit and then try to refuel a system that is going to operate at a much lower pressure.

I would say that there is a greater incentive to look at slush hydrogen for the National Aerospace Plane than there is for an OTV.

I am aware of the work that is being done for the NASP, and my recommendation would be that we just watch them. If it starts to look like slush utilization could be attractive for other NASA space systems, then we should consider what the content of our program in this area should be.

I guess I would also recommend that we don't do anything in addition to the work being supported by the NASP.

The low vapor pressure tankage for OTV's is only a concept at this point. It looks like an interesting concept, but it is not clear that we need to address fluid-handling problems yet.

It looks like, from the depot point of view, the low-pressure OTV tankage concept presents a significant problem for the resupply system.

What I was trying to suggest was that if you wanted a space-based OTV that operated with low pressure tankage, you should do the propellant conditioning on the ground and transport slush or at least highly sub-cooled liquid to orbit.

You still might want to transport slush to orbit just because it minimizes the size of the tanker vehicle.

Certainly, for the Shuttle, we are going to have volume-constrained payloads for the tankage we are interested in, so there is some incentive to have a higher density fluid.



General Dynamics has done some trade studies on this issue. Taking into account all the various options for ground conditioning or on-orbit conditioning, using slush, low-pressure liquid, or 15 to 20 psi saturated liquid, we concluded that low-pressure liquid offers you design and handling advantages over slush, and we did not recommend transport of slush for the low pressure OTV.

There still might be some advantages to having a low pressure depot, even though you might have an OTV with a nominal operating pressure of 15 or 20 psi. It certainly would make it easier to transfer the cryogenic liquids.

That is a valid conclusion, assuming you are pumping the liquids between the tanks.

My concern is that even though low-pressure tankage shows a benefit to the OTV, it looks to me like it adds a lot of complication to the rest of the propellant supply systems.

I would not try to implement it in an experiment right now.

## VII. ADVANCED TECHNOLOGY INSTRUMENTATION

### A. Quantity Gaging

#### Benefit:

- Determine spacecraft resupply effectiveness and depot replenishment need

#### Issues:

- Accuracy in Low-G environment
- Compatibility with cryogenics

#### Experimental Approach:

- Get-away special Shuttle experiment has been proposed by Boeing to investigate basic fluid behavior as it effects gauging techniques
- Ground-based system tests could be followed by in-space demonstration of selected instruments on COLD-SAT

#### Current Program:

- JSC is supporting two parallel instrument development efforts at Ball Brothers
- MIT, via Boeing and NASA Headquarters grants, is studying the physics associated with radio frequency, inductive, nuclear, and ultrasonic gaging techniques

### Discussion

We heard a couple of presentations on quantity gauging yesterday; is anyone aware of any other related work? I think it is generally agreed that this is something that the agency needs to support, and if we have sufficiently developed instruments, the flight experiment would be a good place to demonstrate them.

One thing that should be discussed and included in the program is some sort of visualization technique.

Possibly the use of fiber optics?

The COBE dewar incorporates fiber optics. A hermetically-sealed, optical fiber feed-through was incorporated into the vacuum vessel, but the fibers went to the instruments in the vacuum and not to the inside of the cryogen tank. Therefore, a hermetically-sealed, optical fiber feedthrough was not developed for cryogenic temperatures.

Is this a technology issue, or is it just a way to get better scientific information? Is this instrumentation something we should be considering for the operational systems, or is it just something that would enhance our experiment?

I think that it would be only scientific.

What we are trying to identify? Are there technologies that should be developed for operational systems as well?

MIT is performing studies on gauging techniques.

Is that the work Boeing is supporting with IRAD funding? There are also some NASA grant funds.

Does the grant funding come from NASA Headquarters?

Yes.

Our intention here is to try to make people aware of what work is going on, but, by the same token, if the work is proprietary, then this is not the proper forum for the disclosure of that kind of information. I knew that you were supporting that work with company funds; I was not aware that there was a NASA grant for it also.

## **B. Leak Detection**

### Benefit:

- Safe system operation

### Issues:

- Compatibility with cryogenics

### Experimental Approach:

- Ground-based system tests could be followed by in-space demonstration of selected instruments on COLD-SAT

### Current Program:

- Non-cryogenic techniques have been developed and in-space experimentation planned
- No cryogenic effort underway

## Discussion

There is some leak-detection instrumentation work that is going on at Marguardt. I invited them to participate in the work shop, but they decided not to come. I believe their work is being supported by the military.

It is a Rocket Propulsion Laboratory (RPL) contract. I am not sure what the report status is, but the basic work was completed a year or so ago. They have been working on integrating it into the Spartan satellite which was close to launch, but is now going to fly in 1992. It is just going to be an acoustic measurement test.

To give the group a little background, the leak-detection technique is based on an acoustic technique; it listens for strange sounds. The experiment that is going to fly is not actually a leak-detection system; it's going to measure the background environment on the Shuttle, so they can then design a smart ear that filters out the background noise and only listens for the hisses associated with leaks.

In my discussions with the Marguardt people I felt that they think it's only an engineering design problem to adapt the concept to cryogenic systems. Typically, the instrument would have a direct coupling to the line, valve, or whatever it is you want to listen to, and that would be a thermal short for a cryogenic system. The thinking is that they could come up with techniques to minimize the heat leak for a cryogenic system. I'm not aware of any other work that's being done in this area.

There is a new technique used in the nuclear industry where you can detect leaks by vibration monitoring. The system is characterized during normal conditions so you know what natural frequencies are normal, and then the sensors are used to detect off-nominal vibration frequencies.

### **C. Mass Flow Metering**

#### Benefit:

- Allows monitoring of transfer system performance
- Integration of flow measurement provides alternative to quantity gaging

#### Issues:

- Achievable accuracy
- Compatibility with cryogens

#### Experimental Approach:

- Ground-based testing will be followed by integration of selected instrument into COLD-SAT to provide data on transfer system performance

#### Current Program:

- NBS has a program funded by ARC to develop Venturi and turbine type superfluid helium flow meters
- MSFC is funding work at NBS on vortex meters
- Lewis has entered into a contract with Quantum Dynamics to develop a liquid hydrogen mass flow meter

#### Discussion

The general thinking is that quantity gauging is a real key technology for some of the applications. However, it is not obvious that we will be successful in meeting that need. An alternative approach is to use flow meters with an integrating technique, and try to detect leaks to maintain a fluid inventory.

What about the fluid that you're deliberately venting?

That's part of the flow metering. The philosophy we are going to use on our flight experiment involves not only metering the liquid flow between tanks, but also the venting, including the Thermodynamic Vent System (TVS) flows.

The thing that really kills you with that approach is if you've got a leak.

It's going to have to be a pretty major leak before you'll detect anything.

NBS is developing flow instrumentation for helium systems.

Do you see any reason why that technology could not be applied to the systems we have been discussing here?

No.

How is that being supported; is that through an interagency agreement with Ames Research Center?

Yes.

We have a facility at NBS for calibrating flow meters.

## VIII. MISCELLANEOUS

### A. Pool and Film Boiling

#### Benefit:

- Understanding of basic heat and mass transfer processes

#### Issues:

- Effect of acceleration environment

#### Experimental Approach:

- Ground-based experiments using aircraft followed by in-space testing on the Shuttle (mid-deck or gas can)

#### Current Program:

- The space nuclear power program is supporting both analytical and experimental work at Battelle Pacific Northwest Laboratory

### Discussion

I would like to suggest that this area is another one of those things that falls more into the area of a scientific investigation rather than something that should be included in a technology program. Low-gravity boiling phenomena is something that all of us are interested in; we are all supporters of this type of scientific experiments, but in general and for the cryogenic systems we are concerned about, the heat fluxes will be so low that we will be below the threshold of boiling.

Evaporation and condensation at the liquid-vapor interface, rather than any type of boiling, will be key processes controlling the transfer system performance. Those heat and mass transfer issues have been adequately addressed elsewhere.

### B. Low Pressure Tankage

#### Benefit:

- Minimize orbit transfer vehicle weight

#### Issues:

- Impact on vehicle design
- Depot and tanker operations (necessity to provide low vapor pressure propellants for supply to OTV)

- Future studies must consider overall OTV resupply system operating scenario

Experimental Approach:

- Ground-based testing of low pressure tankage to help quantify concept benefits.

Current Program:

- General Dynamics has completed a study which quantified the benefits of low-pressure tankage for the OTV only

Discussion

There are design and fabrication techniques that will allow tank fabrication from thin gauge materials. However, that is a separate issue, and not related to fluid management.

**C. Component and Control System Life**

Benefit:

- Multi-year depot operation with minimal maintenance

Issues:

- Reliability
- Life

Experimental Program:

- Ground-based testing as part of transfer system experimental program

Current Program:

- Lewis is supporting the development of multi-cycle liquid hydrogen latching valves at Moog

Discussion

None.

## APPENDIX A

### LIST OF ACRONYMS

AFAL	Air Force Astronautics Laboratory
AFWAL	Air Force Wright Aeronautical Labs
ARC	Ames Research Center
COBE	Cosmic Background Explorer
EVA	Extravehicular Activity
GDC	General Dynamics Convair
GSFC	Goddard Space Flight Center
IR&D	Independent Research and Development
IRAS	Infrared Astronomical Satellite
JSC	Johnson Space Center
KSC	Kennedy Space Center
LAD	Liquid Acquisition Device
LDEF	Long Duration exposure Facility
LeRC	Lewis Research Center
LMSC	Lockheed Missiles and Space Company
LOX	Liquid Oxygen
MLI	Multi-Layer Insulation
NBS	National Bureau of Standards
NPSP	Net Positive Suction Pressure
OAST	Office of Aeronautics and Space Technology
PODS	Passive Orbital Disconnect Struts
PRSA	Power Reactant Storage Assembly
RCS	Reaction Control System
RF	Radio Frequency
RPL	Rocket Propulsion Laboratory
SBOTV (OTV)	Space-Based Orbit Transfer Vehicle
SDI	Strategic Defense Initiative
SHOOT	Superfield Helium On-Orbit Transfer
SIRTF	Space Infrared Telescope Facility
TVS	Thermodynamic Vent System



## APPENDIX B

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16. Abstract  The Cryogenic Fluid Management Technology Workshop was held April 28, 29, and 30, 1987, at the NASA Lewis Research Center in Cleveland, Ohio. The major objective of the workshop was to identify future NASA needs for technology that will allow the management of subcritical cryogenic fluids in the low-gravity space environment. In addition, workshop participants were asked to identify those technologies which will require in-space experimentation and thus are candidates for inclusion in the flight experiment being defined at Lewis. The principal application for advanced fluid management technology is the Space-Based Orbit Transfer Vehicle (SBOTV) and its servicing facility, the On-Orbit Cryogenic Fuel Depot (OOCFD). Other potential applications include the replenishment of cryogenic coolants (with the exception of superfluid helium), reactants, and propellants on board a variety of spacecraft including the Space Station and space-based weapon systems. The last day of this workshop was devoted to a roundtable discussion of cryogenic fluid management technology requirements by 30 representatives from NASA, industry, and academia. This volume contains a transcript of the discussion of the eight major technology categories.					
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